FORAGING BEHAVIOR OF DAIRY CATTLE IN A PASTURE-BASED SYSTEM WITH AUTOMATED MILKING

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ABSTRACT

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Automated milking systems (AMS) offer the potential to increase production and decrease labor costs, providing an option for small farms to remain competitive in today's dairy industry. The success of AMS in a pasture-based feeding system is contingent upon careful management of grazing rotation and cow traffic to entice voluntary milkings. A better understanding of how cows respond to the pasture environment is important for improving management in this context. Our first objective was to evaluate cow responses to both travel distance between paddocks, and forage species heterogeneity among paddocks. Cows increased grazing bout length ($P < 0.02$) and decreased bout frequency ($P < 0.002$) with greater traveling effort. Milk yield was not affected ($P = 0.52$) by distances between paddocks, however, greater overall distance walked daily decreased ($P < 0.009$) milk yield. Forage species heterogeneity among paddocks had no effect ($P > 0.05$) on behavior or milk production. Our second objective was to determine whether cows exhibit temporal preference for certain species mixtures based on predicted increases in water-soluble carbohydrates (WSCs) during evening hours. Contrary to expectation, cow preferences tended not to be based on time of day ($P > 0.05$), but may have been skewed by unequal biomass availability across contrasting forage species mixtures. Our final objective was to examine grazing behavior in two feeding systems, and between two cattle breeds. Cows fed partial total mixed ration (pTMR) spent less time grazing ($P < 0.01$) than those not fed pTMR. United States Holsteins had greater milk yield ($P < 0.01$) than New Zealand Friesians. No other variables differed ($P > 0.05$) between feeding systems or breeds.

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ABBREVIATIONS

AMS	Automated Milking System
BW	Body Weight
CP	Crude Protein
DIM	Days in Milk
DM	Dry Matter
GPS	Global Positioning System
HSR	High Stocking Rate
LSR	Low Stocking Rate
NDF	Neutral Detergent Fiber
NZF	New Zealand Friesian
NSC	Non-Structural Carbohydrate
PC	Pasture + Concentrated feed supplement
pTMR	Partial Total Mixed Ration
RPM	Rising Plate Meter
SCC	Somatic Cell Count
SEM	Structural Equation Model
TMR	Total Mixed Ration
USH	United States Holstein
WSC	Water-Soluble Carbohydrate

INTRODUCTION

Pasture-based animal production has been the norm for over 6,000 years. Only in the past century, with the advent of highly mechanized crop harvesting, have producers begun to switch to confinement-based systems. However, recent increases in feed and fuel prices have prompted some dairy farmers to return to pasture-based production systems. A major concern regarding this method of production is remaining competitive with high-input, confinement dairies. Modern technologies such as Automated Milking Systems (AMS) have the potential to improve pasture-based production, but only with strategic management of animal movements. For decades, ecologists have predicted animal movements based on forage availability and quality, yet these models are not often applied to livestock, particularly not on a broad spatial scale. It is important to understand how foraging principles apply in pasture-based systems. Managing for feeding patterns that improve an animal's energy efficiency will also improve production. The first chapter provides a review of foraging ecology literature, as well as studies that have previously tested foraging models on large herbivores. It also reviews the current literature on AMS and its varying success in pasture-based systems.

The second chapter describes how dairy cows respond, both in their movements and use of the AMS, to broad-scale heterogeneity in a pasture environment. Traditional foraging ecology suggests that searching cost plays an important role in how long an animal remains at a feeding site. In short, movements are dictated by net energy intake. Some foraging ecologists also suggest, for large herbivores in particular, a drive for variety in the diet can also motivate movements, but this is not well tested at a broad scale. With this in mind, we examined distance and forage variety as two potential variables for influencing cow performance.

Some evidence suggests that certain forage species exhibit dramatic temporal fluctuations in water-soluble carbohydrate (WSC) content, causing grazing animals to favor these species at particular times of the day. In the third chapter, we further investigate diet variety, to determine whether temporal variations play a role in cows' selectivity for a high-WSC grass. In turn, we determine how this influences broad-scale movements and AMS performance.

In lieu of adopting fully pasture-based systems, some farmers have chosen to use an intermediate feeding system, supplementing a pasture diet with pre-harvested forages, such as silage, hay, and grain. This hybrid system reduces susceptibility to production loss while still reaping some of the benefits of pasture-based farming. Some farmers also choose to use animals that are bred for high performance in a particular feeding system. In chapter 4, we examine the performance of two cattle genotypes, New Zealand Friesians and United States Holsteins, in a fully pasture-based system and in a partially pasture-based system. Overall, we expect our results to provide valuable insights into environmental factors that affect animal behavior and performance in the context of AMS and pasture-based feeding systems.

CHAPTER 1

LITERATURE REVIEW

INTRODUCTION

Resource acquisition is a vital biological process, highly relevant in both theoretical and applied areas of study. Foraging strategies have long been a topic of interest to behavioral ecologists, because energy intake often demands a considerable time investment by foragers (MacArthur and Pianka, 1966; Stephens and Krebs, 1986). In agriculture, understanding foraging behavior is important for addressing a variety of issues from pest control to livestock production to resource conservation and management. In response to the demands of the modern food industry, animal producers are showing a renewed interest in applying foraging principles to management practices (Bailey and Provenza, 2008).

Over the last half-century, agricultural systems have undergone rapid changes in order to meet the nutritional requirements and societal demands of an ever-increasing human population (Rosenzweig and Parry, 1994). In many cases, sometimes unintentionally, biodiversity and product quality have been sacrificed for production efficiency (Tilman et al., 2001; Tscharntke et al., 2005). Dairy farms in the central and western United States continue to increase in size and decrease in number. In response to a rising demand for dairy products, novel technologies, such as voluntary robotic milking, have been developed to increase milk yield and decrease labor requirements. By improving labor and production efficiency, this technology offers small- and medium-sized farms, including some pasture-based farms, an opportunity to remain profitable in a highly competitive market.

The integration of robotic milking and rotational grazing may be an alternative option to preserve product quality while reducing environmental impact, but current research suggests that

this combination tends to reduce milk yield (Garcia and Fulkerson, 2005). This loss is often attributed to poor control over voluntary cow traffic. Using principles from foraging ecology, livestock growers may be able to improve management of animal movements and forage intake in order to maximize production in the context of grazing and voluntary milking.

Ecological theory predicts that foraging decisions of cows and other animals are largely based on maximizing energy gain. As the energetic cost of obtaining food increases, animals must compensate by increasing energy intake (Stephens and Krebs, 1986). Consistent with this idea, large herbivores are expected to graze a particular patch of forage long enough to make up for the energy expended in traveling to that patch (Charnov, 1976; MacArthur and Pianka, 1966). When a variety of food items are available in a habitat, animal behaviors may not always conform to this predicted relationship between cost and intake. A heterogeneous foraging environment may cause an animal to seek novel food items more frequently, in order to increase variety in its diet (Bailey and Provenza, 2008).

In this review, I provide a description of foraging principles that may have valuable implications for pasture dairy management in robotic milking systems. First, I describe Optimal Foraging Theory, specifically the "prey" and "patch" models, which provide a framework for predicting diet choices and habitat use by foragers. I briefly summarize the digestive rate foraging model, which posits that an animal's forage intake is limited by the speed of digestion. Next, I introduce the satiety hypothesis, which seeks to explain situations in which foraging behaviors deviate from optimal foraging predictions, particularly in habitats with heterogeneous forage distribution. For each foraging model, I provide empirical examples to support theory. Lastly, I describe voluntary milking in further detail, citing previous studies that have explored the potential for integrating this system with grazing.

FORAGING ECOLOGY AND THEORY

Optimal Foraging Theory

In 1966, MacArthur and Pianka first described foraging models to predict diet breadth and patch use by foragers. The diet model (or prey model) predicts which prey items a forager should include in its diet, while the patch model predicts a forager's residence time in a given assemblage of prey items (i.e., patches). Both models posit that foragers will maximize fitness by maximizing the rate of net energy intake (MacArthur and Pianka, 1966). Rate maximization is a central theme of Optimal Foraging Theory, although these two original models have since expanded into a diverse suite of models, each with a unique set of constraints (Stephens et al., 2007).

Foraging theory makes three basic assumptions regarding the nature of foraging behavior. First, it assumes that foragers can perceive differences in forage types, and can actively decide whether or not to pursue a particular forage type, or whether to leave a given foraging patch. Next, it assumes that foraging behaviors are governed by Darwinian principles of natural selection. That is, current foraging behaviors exist because they increase fitness through the forager's application of a choice principle (e.g., maximize, minimize) to a currency (e.g., energy, time). Lastly, it assumes that a forager experiences environmental constraints. For instance, the nature of the foraging environment may result in sequential encounter of prey items or patches, rather than encountering multiple prey items at once (Stephens and Krebs, 1986).

Patch and prey models are similar, but not identical in their treatment of the forager-forage relationship. Both models consider a rate of encounter for a given patch or prey type, and a time investment involved in consuming the forage item. The prey model focuses on discrete forage items that are completely consumed or avoided. For a given forager, a prey type should

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either always be consumed upon encounter, or never consumed upon encounter, depending on the net energy yield of that particular prey type. Below a minimum energy payoff, potential prey items should be excluded from the diet (MacArthur and Pianka, 1966; Stephens and Krebs, 1986).

Scaling up to a landscape level, the patch model, as its name would suggest, examines a forager's decisions within patches of clumped or unevenly distributed food items. Within a given patch of food items, foragers are expected to experience diminishing returns: the density of food items, and thus the rate of encounter should decrease the longer the forager spends in the patch. When the intake rate for a given patch – its marginal value – falls below the overall rate of gain across patches (i.e. the habitat), it is no longer advantageous for a forager to remain in that patch. Furthermore, as inter-patch distance is increased, minimum marginal threshold should decrease to compensate for energy expenditure during travel. Simply put, efficient animals should stay in a patch longer, when they traveled farther to get there in the first place (Charnov, 1976; MacArthur and Pianka, 1966).

Tests of Optimal Foraging Models on Large Herbivores

Large grazers have dynamic relationships with both managed and unmanaged grasslands. Patch depression, and in turn, plant growth rates play a key role in determining animal movements among patches. The amount of forage consumed within a patch, as a function of patch residence time is often described as the "gain function" for that particular patch (Searle et al., 2005). Within patches, domestic cattle (*Bos taurus*) take smaller bites as the sward is depleted, resulting in decreased forage intake rates over time (Laca et al., 1994b). Approximately 50% of sward height is depleted with each successive bite (Cangiano et al., 2002). This is

consistent with Charnov's assumption of diminishing returns – an important premise for optimal patch use models (Charnov, 1976). Following the predictions of patch models, a broad range of non-domestic ruminants tend to exhibit increased patch residence time in response to increased travel requirements between patches (Kotler et al., 1994; Shipley and Spalinger, 1995; Searle et al., 2005). More recently, this response was also demonstrated in domestic cattle (Utsumi et al., 2009).

In all of these cases, a patch was defined at the relatively fine scale of "feeding station," that is, an area of forage small enough to be depleted without requiring any travel (Searle et al., 2005; Ruyle and Dwyer, 1985). However, a "patch" may be perceived at a number of different spatial and temporal scales: the area covered in a single bite, a feeding station of several bites, a complete grazing bout at a given feeding site, or long-term migratory movements within the animal's home range (Sneft et al., 1987; Bailey et al., 1996; Kotliar and Wiens, 1990). Cattle and ewes exhibit selectivity between different feeding stations within a feeding site (Rook et al., 2004), and Laca (1998) demonstrated that cattle were capable of forming a spatial reference memory of multiple feeding sites within their range.

Understanding the relationship between fine and broad scale foraging decisions is becoming an important challenge for foraging ecologists, but empirical studies of this topic are scarce. Patch distribution and quality may modify long- and short-term foraging decisions. For instance, sheep were more inclined to abandon poor quality hay to walk for high quality hay when the reward-distance ratio was high (Dumont et al., 1998). Another study indicated that context of patches within a spatial hierarchy explained patch residence time for grizzly bears and mule deer along with patch density and distance between patches (Searle et al., 2006). This suggests that animals may base foraging decisions on both localized heterogeneity and broad

heterogeneity across the habitat. Attempts to apply optimal patch use models to broad foraging scales remain fairly uncommon.

The Digestive Rate Model

Related to Optimal Foraging Theory, the Digestive Rate Model seeks to predict foraging behaviors based on the premise that foragers should make decisions that will maximize the rate of energy intake. However, while optimal prey and patch models posit that forage ingestion rate is the limiting factor on net energy gain, the Digestive Rate Model suggests that digestion rate is more limiting. Highly indigestible food content, such as fiber from plant materials or calcium carbonate from shells, may slow the rate of passage and indirectly limit the rate of forage consumption (Verlinden and Wiley, 1989). Two concurrent studies empirically tested the Digestive Rate Model, finding that the red knot, a mollusk-eating shorebird, selected highly digestible prey rather than the largest, most profitable prey items (Van Gils et al., 2005a; Van Gils et al., 2005b).

While ruminant nutritionists have long thought that gut distension resulting from high-roughage diets may limit energy intake (Grovum, 1988), few foraging ecologists have extensively explored the idea of digestive limitation in the context of large mammal decision-making. In the process of foraging, biting and chewing mark the transition from ingestion to digestion. For roe deer, the rate of oral processing limited intake more than overall encounter rate (Illius et al., 2002). Fryxell (1991) suggests that the inverse relationship between fiber content and forage biomass (Van Soest et al., 1978) necessitates a trade-off for large grazers. In patches with low biomass and high forage quality, energy intake should be limited by ingestion rate, whereas high biomass but low forage quality patches should be limited by digestion rate.

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Following the predictions of this model, both wapiti and cattle showed preference for patches with both intermediate biomass and maturity (Wilmshurst et al., 1995; Wallis De Vries and Daleboudt, 1994; Ganskopp and Bohnert, 2009). It is unclear, however, whether this apparent preference was mediated by a need to maximize protein intake rather than energy gain (Langvatn and Hanley, 1993). In some situations, energy maximization may not be the primary factor governing foraging decisions.

The Satiety Hypothesis

Maximizing the rate of energy gain may be a key driver behind an animal's foraging decisions, but in some cases, animals may deviate from this rate maximization principle to increase diet diversity and nutrient balance. Provenza (1995) suggested that large herbivores should select a variety of plants in an effort to avoid consuming too much of any one plant toxin. When forage is abundant, foragers can afford to be more selective, pursuing novel food items to make up for nutrient imbalances (Bailey and Provenza, 2008). For instance, Thomson's gazelles are restricted by rate of ingestion at low levels of forage availability, but when forage is abundant, intake appears to be constrained by post-ingestive feedbacks (Wilmshurst, 1999). Assuming real foragers lack perfect knowledge of how to spatially and temporally allocate foraging behaviors, they constantly experiment and reevaluate the amount and types of forage consumed (Forbes, 2000), as well as the locations where it can be harvested (Laca, 1998; Provenza et al., 2003).

Post-ingestive feedbacks are central to both the digestive rate model and the satiety hypothesis. However, while the digestive rate model seeks to explain limitations on energy intake, the satiety hypothesis focuses on mechanisms of diet selection and mixing. It has been

well demonstrated that the physiological consequences of forage intake can alter subsequent foraging behaviors in order to maintain long-term homeostasis (Forbes, 2000). Temporary aversion, or reduced preference for a specific food type following its ingestion, is an important principle of the satiety hypothesis (Bailey and Provenza, 2008). Defenders of the satiety hypothesis attribute alternating patterns of forage preference to temporary nutrient aversions. Sheep exhibited a preference for legumes in the morning and grasses in the afternoon, although the latter is less nutritious (Newman et al., 1992; Parsons et al., 1994). This aversion likely results from the buildup of organic acids and ammonia in the rumen environment during fermentation of highly digestible forage (Cooper et al., 1995). Sheep also perceive post-ingestive differences between carbohydrate and protein, and modify preference to maintain a relatively constant ratio of intake (Villalba and Provenza, 1999). Plant secondary metabolites, however, may modify this response by altering palatability (Villalba et al., 2002).

Sheep and cattle tend to select for variety in their diets, with about 70% partial preference for legumes over grasses (Marotti et al., 2002a; Rutter, 2006). This preferentially selected ratio holds, regardless of the animal's lactation state (Parsons et al., 1994) or the ratio of legumes to grasses in the sward itself (Rutter et al., 2004). The inclusion of some grasses in the diet, even when legumes are abundant enough to fulfill herbage mass requirements, suggests that grasses may be necessary to satisfy certain nutrient requirements or toxin aversions (Chapman et al., 2007). Furthermore, intake rate maximization alone fails to explain the selection of mixed diets in large herbivores, since both sheep (Penning et al., 1991; Marotti et al., 2002a) and cattle (Rutter et al., 2004) can consume legumes more quickly than grasses (Rutter, 2006).

Most tests of alternating forage preferences and aversions have been conducted in adjacent monocultures, and at a small-scale – usually at the level of "feeding stations" – but the

satiety hypothesis may also explain large-scale movements across more diverse patches within an animal's habitat (Bailey and Provenza, 2008).

Criticisms of the Satiety Hypothesis

The satiety hypothesis has received criticism from some foraging ecologists. One major criticism is the lack of clarity on whether this hypothesis is truly distinct from the 'giving-up rules' or 'constraints' which are part of optimal foraging theory (Van Wieren et al., 2008). Belovsky (1978) demonstrated that moose alternate between energy-rich plants, and energy-poor but sodium-rich aquatic plants in order to meet nutrient requirements. Belovsky argues, however, that simple optimization models can account for this shifting diet preference, provided the model does not assume simultaneous search for all food classes.

Although the satiety hypothesis has received support from some highly controlled studies, using small-scale definitions of forage "patches," experiments that mimic more natural, diverse systems tend to yield no evidence for it. When goats were given the choice between two contrasting forages following a homogeneous conditioning diet, they tended to minimize plant secondary metabolite intake rather than varying their diets or maximizing intake (Jansen et al., 2007).

INTEGRATION OF FORAGE HETEROGENEITY INTO MANAGEMENT OF PASTURE-BASED PRODUCTION SYSTEMS

When considering foraging behaviors and resource utilization, one must acknowledge the spatial heterogeneity of natural landscapes, both managed and unmanaged. Most, if not all grassland communities, even pasture monocultures, are heterogeneous in some aspects. Resource

heterogeneity allows foragers to preferentially select above-average patches, thus increasing energy and nutrient intake beyond what they could achieve by grazing randomly (Laca, 2008). Animal response to spatial heterogeneity is a growing topic of interest among both grazing ecologists and livestock producers. Intentional implementation of heterogeneity in the foraging landscape could benefit livestock farmers facing demands for increased yet sustainable production efficiency.

Large herbivores perceive heterogeneity in the grazing landscape, and also contribute to its perpetuation (Chapman et al., 2007). Through defecation and urination, animals leave patches of nutrient-rich soil, and selectively avoid grazing these patches, allowing for increased plant growth (Cid and Brizuela, 1998; Hirata et al., 2011). Furthermore, large grazers and browsers create trails to allow for easy travel through frequently used foraging sites (Bailey, 2005). When forage is more abundant than the demands of the herd, herbivores further augment patchiness through increased selectivity, particularly when a foraging site is continuously accessible (Provenza et al., 2003, 2006). Removal of animals to allow regrowth after sward biomass has been depleted by roughly 1/3-1/2 can mitigate the effects of animal selectivity on patch heterogeneity (Hirata et al., 2011; Parsons and Dumont, 2003). Increasing the stocking rate, or the number of animals grazing per unit area, can also reduce patchiness by forcing animals to be less selective (Provenza et al., 2003, 2006). Many pasture-based production systems in the UK, New Zealand, Australia, and Ireland control for fine-scale heterogeneity by rotationally grazing animals on different paddocks (Marotti et al., 2002b; Chapman et al., 2007).

In pasture-based animal production systems, managing for heterogeneity at the paddock scale may be a useful strategy for achieving desired behavior and production responses. It is known that large herbivores exhibit partial preference for legumes, but still include grasses when

both are available in adjacent monocultures (Rutter, 2006). Sheep maintain this partial preference regardless of whether they are grazing a mixed sward or adjacent monocultures (Champion et al., 2004), suggesting that they perceive heterogeneity at multiple spatial scales. Furthermore, when sheep are grazing adjacent monocultures of grasses and legumes, they transition between the two plots with increasing frequency throughout the day (Champion et al., 2004). In a ten-day period, lambs that grazed with their mothers on this pasture arrangement gained significantly more weight than those grazed on a mixed sward of both species (Champion et al., 2004).

Currently, many pasture-based production systems use mixed-species swards of grass and clover. Some debate exists over whether a mixed sward is the best option for maximum production (Chapman et al., 2007). On one hand, inclusion of clover at a proportion of 0.5 in a clover-grass mixture achieves a milk yield 33% higher than that achieved on a grass monoculture, and only 5% lower than on a clover monoculture (Harris et al., 1997). Furthermore, the inclusion of some grass in the diet also reduces some of the negative consequences (e.g., bloat) of a diet with a high proportion of legumes. On the other hand, grass is known as a superior light competitor when grown with clover (Woledge, 1978; Woledge and Dennis, 1982), and ruminants selectively include more clover than grass in the diet (Rutter, 2006), so desirable proportions of clover are difficult to maintain. Chapman et al. (2007) propose eliminating inter-species plant competition by grazing grass and legumes in adjacent monocultures, similar to the monoculture experiments described above. Rutter et al. (2001, 2003), support this idea, but suggest that simultaneous grazing of both species is not necessary, and similar production can be achieved by alternating "temporal grazing allocations" that is, grazing each monoculture type in a sequential manner, at different times of the day.

Supplement rewards have also been examined as a method for managing heterogeneity and improving pasture utilization in less desirable paddocks. Strategically placed salt (Williams, 1954), molasses, and water (Bailey, 2005) have all been used to draw livestock to less desirable foraging sites. Once at these sites, animals are more likely to consume forage, since travel investment between the supplement and the surrounding forage is negligible. A problem with this approach is that supplement addition often overcorrects for under-utilized forage, causing animals to concentrate grazing efforts in the area immediately surrounding a supplement (Laca, 1998, 2000). Randomizing the spatial and temporal placement of supplements may cause a more even distribution of animals across feeding sites, though this response to randomization only holds when forage is abundant (Distel et al., 2004).

There is ample empirical evidence to suggest that large herbivores perceive and respond to heterogeneity at multiple scales. Extreme heterogeneity and uneven grazing distributions are largely undesirable, as they can lead to landscape degradation and localized plant extinctions. Controlled spatial or temporal heterogeneity, however, can be used to manage animal intake and production, while still conserving grazed landscapes.

AUTOMATED MILKING

Development and Implementation of Automated Milking Technology

Toward the end of the 20th century, increasing farm sizes and labor demands led to the development of automated milking technology (de Koning and Rodenburg, 2004; de Koning, 2010). Since the first automated milking unit was installed in the Netherlands in 1992, roughly 11,000 dairies in 25 different countries have adopted automated, robotic milking systems (de Koning, 2011). An automated milking system (AMS), or "robotic milker", can milk a cow

without direct human intervention, as all steps of the milking process are completely automated. When a cow enters the AMS unit, she receives a reward of feed concentrate, the quantity of which is determined on an individual basis. The unit then locates and cleans the teats, attaches teat cups, and, when milking is complete, applies a disinfectant solution. The unit is equipped with a self-cleaning mechanism, and records animal health and milk quality metrics. Milk is collected from each cow individually before transfer to the main tank, and can be diverted if the unit detects contaminants or a high somatic cell count.

A primary factor in managing a successful AMS is providing motivation for the cows to visit the unit on a voluntary basis, multiple times per day (Rossing et al., 1997; de Koning and Rodenburg, 2004). Since individual animals have the potential to be milked more times per day by an AMS unit than they would by manual labor in a conventional system, the AMS has the potential to increase milk yield. The combination of increased milking frequency and concentrate consumption may increase milk yield by up to 35% (de Koning and Rodenburg, 2004).

Originally, early versions of AMS were designed for small family farms with between 50 to 150 lactating animals, although some farms with herds of up to 500 have begun to adopt AMS (Svennersten-Sjaunja and Pettersson, 2008). Most farmers cite labor reduction, improved lifestyle, and increased milk yield as their primary motivation for investing in AMS (Hogeveen et al., 2004). Indeed, labor hours are often reduced by up to 20% after the adoption of AMS (de Koning and Rodenburg, 2004).

Integration of Automatic Milking and Pasture Grazing

While AMS has proven to be a successful in confinement operations, it may pose some problems in pasture-based systems. Due to the voluntary nature of AMS, cow traffic has a major

influence on the success of the operation. The importance of this factor is amplified in a pasture-based system, when cows are required to travel to and from paddocks to acquire food. Oftentimes, pasture-based AMS operations experience lower milking frequencies than confinement operations, and must allocate additional labor to fetching cows from the pasture (Salomonsson and Sporndly, 2000; van Dooren et al., 2004). This reduction in milking frequency and production appears to be inversely proportional to the number of hours that cows are allowed to graze per day (Ketelaar-de Lauwere et al., 1999; Utsumi, 2011).

Offering food and water incentives is the most effective method of encouraging movement in a pasture system (Jago et al., 2002). At least two fresh pasture breaks per day force the animals to leave depleted paddocks and visit the AMS at least once (Davis et al., 2007). Providing three fresh breaks per day further increases traffic, milking frequency, and production (Lyons, 2011). While fresh pasture breaks can motivate movement, high biomass can decrease the incentive to leave a paddock. In one study, milking frequency was an inverse function of sward height (Ketelaar-de Lauwere et al., 2000). Increased distances between paddocks and the AMS may also contribute to decreased milking frequencies. Continued improvement of movement incentives in pasture systems is necessary to reduce the labor of fetching cows, which otherwise offsets the goal of labor reduction with AMS.

CONCLUSIONS

The rules governing foraging behavior are well understood and have been tested in a variety of species. Theory suggests that maximizing energy intake is the primary goal behind most, if not all, foraging decisions. Large herbivores are well adapted to survive on forage with disproportionally high biomass relative to its nutritional value. Due to the nature of their diets,

ruminants may deviate from traditional maximization rules in order to minimize toxins or other negative effects of ingesting a large amount of a given forage. In dairy operations that integrate grazing and AMS, food incentives such as pasture and supplements appear to be the best method of increasing cow traffic throughout the system. A better understanding of the foraging rules that determine broad-scale movements of dairy cows may aid in the development of strategies for encouraging movement and increasing milk yield. If AMS efficiency can be improved within the context of pasture-based dairy farming, this combination would offer a potentially cost-effective alternative to small farmers.

In the following chapters, I explore environmental and behavioral factors that may influence voluntary AMS use by cows in the context of a pasture-based feeding system. In chapter 2, I empirically test two foraging theory predictions, examining the effects of distance to the pasture and heterogeneity of pasture plant species on cow movements. Chapter 3 further explores pasture heterogeneity, but examines whether cows exhibit preferences for certain species depending on time of day. In chapter 4, I compare two different genotypes of Holstein-Friesian cattle in the context of two feeding systems: an 80% pasture diet and a 52% pasture diet. Both biotic factors (e.g., feed source and variety) and abiotic factors (e.g., climate, time of day, spatial restrictions) may play a role in cow grazing behaviors.

CHAPTER 2

EFFECTS OF DISTANCE AND BROAD-SCALE HETEROGENEITY ON FORAGING DECISIONS OF DAIRY CATTLE IN A FREE-TRAFFIC PASTURE SYSTEM

Abstract

Energetic trade-offs and variety in forage types may modify cattle movements and foraging decisions at the habitat level. In a pasture-based dairy system with automated milking (AMS), understanding how cows respond to changes in the pasture environment is important for managing cow traffic. We explored how traveling distance between paddocks and variety in pasture species mixtures influenced grazing behaviors, milking frequency, and milk production in an AMS. Two herds of 48 ($\pm$ 4) cows were grazed in two pasture rotation sequences – homogeneous grazing, and heterogeneous grazing – in a crossover design. The homogenous grazing sequence included two breaks per day of the same pasture species mixture, while the heterogeneous grazing sequence included two breaks of different pasture species mixtures. Grazing bout length increased ($P < 0.02$), and grazing bout frequency decreased ($P < 0.002$) with increased travel distances between paddocks. Milk yield was not directly affected ($P = 0.52$) by distances between paddocks, however, overall distance walked by the cows caused a decrease ($P < 0.009$) in milk yield. Furthermore, structural equation modeling detected several significant direct and indirect relationships between environmental factors, internal animal factors, behavior and milk production in this system. Pasture rotation sequence (heterogeneous or homogeneous) had no effect ($P > 0.05$) on grazing behaviors, milking frequency, or milk production, suggesting that cows do not respond to pasture heterogeneity at a broad spatial scale. Abiotic factors such as distance seem to play a more important role in movement decisions at a coarse scale.

INTRODUCTION

Background

Toward the end of the 20th century, increasing dairy farm sizes and labor demands led to the development of automated milking technology. This technology is becoming increasingly popular among farmers across the U.S., Canada, Europe, New Zealand, and Australia (de Koning and Rodenburg, 2004; de Koning, 2010, 2011). A primary factor in managing a successful automated milking system (AMS) is providing motivation for the cows to visit the milking unit on a voluntary basis, multiple times per day (Rossing et al., 1997; de Koning and Rodenburg, 2004). Because individual animals have the potential to be milked more times per day by an AMS unit than they would by manual labor in most conventional systems, the AMS has the potential to increase milk yield. However, the implementation of AMS in a pasture-based dairy may actually lead to decreased milk yield, due to increased walking activity and distance from the milking unit during grazing bouts (Ketelaar-de Lauwere et al., 1999; Utsumi, 2011). Farmers who use AMS in pasture-based production systems face the challenge of manipulating cows' voluntary movements in order to maximize milking frequency and yield.

Perhaps the best method of encouraging an animal to voluntarily move throughout its habitat is to offer a reward in a currency that animals recognize: food. A few recent studies have already examined the effectiveness of food rewards in pasture dairy systems (e.g., Jago et al., 2002). Providing multiple fresh pasture breaks per day, and requiring animals to travel through the milking barn between breaks increases the likelihood that animals will visit an AMS (Davis et al., 2007; Lyons, 2011). Dairy cows are just one of many species that can be motivated by food rewards. Foraging ecologists have long theorized and tested how animals move through

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their habitats based on food availability and energy budget (see MacArthur and Pianka, 1966; Charnov, 1976; Stephens and Krebs, 1986).

According to optimal foraging rules, animals should stay in a "patch," or aggregation of food items, longer when they traveled farther to get there in the first place. In this way, they make up for the energy expended by increasing consumption. "Optimal patch use" has been successfully demonstrated in a host of wild ruminants (Kotler et al., 1994; Shipley and Spalinger, 1995; Searle et al., 2005), but only rarely has it been tested in domesticated livestock (Utsumi et al., 2009). Some foraging ecologists have hypothesized that, in heterogeneous environments, large herbivores may deviate from optimal foraging rules due to satiation on a particular nutrient (Bailey and Provenza, 2008). The "satiety hypothesis" posits that a forager may leave a patch earlier than predicted by optimal foraging rules, in search of novel food items to increase diet breadth, or reduce buildup of plant toxins. Some evidence exists to support this idea, but most empirical tests have involved offering animals free movement between two distinct monocultures of forage species (Newman et al., 1992; Parsons et al., 1994; Marotti et al., 2002a; Rutter, 2006). Realistically, most natural or commercially managed foraging environments would likely include a mixture of species. Furthermore, optimal patch use predictions and satiety hypothesis predictions have usually been tested on only a fine scale of very localized patches, small enough to be consumed in a few bites. It is not known how large herbivores will respond to heterogeneity at a more coarse scale, at the level of distinct paddock types, for instance. Heterogeneity at a more broad scale has the potential to influence large-scale movements (Senft et al., 1987), which could have important implications for livestock grazing management strategies when movement affects production.

Objectives

The objectives of this study were twofold. First, we sought to determine how dairy cows respond to walking requirements of varying distances in a rotational pasture system, and if they follow predictions of optimal patch use models. We predicted that cows should extend residence time in paddocks that were farther away from the milking barn. In turn, we expected that by extending residence time, cows would reduce the frequency of total paddock visits per day, and the frequency of voluntary milkings per day, in response to increased distance. Furthermore, as cows allocated more energy towards traveling, we expected to see a decrease in milk yield. Our second objective was to evaluate cow responses to heterogeneity of plant species between paddocks, in order to assess whether the satiety hypothesis predictions would apply at this broad spatial scale. We expected that animals offered a sequence of pasture breaks that alternated between paddocks of two different species mixtures (heterogeneous grazing) would decrease residence time in paddocks. We also expected that cows grazed on this alternating sequence would show an increased frequency of paddock visits and voluntary milkings.

MATERIALS AND METHODS

Study Site

The study was conducted at the W.K. Kellogg Biological Station (KBS) Dairy in Hickory Corners, Michigan. Prior to the start of this study, protocols were reviewed and approved by the MSU Institutional Animal Care and Use Committee (IACUC). During the study period, the lactating herd included 95 (±4 on any given day) Holstein-Friesian cattle. The farm has 64 ha of pasture, divided into 8 blocks of paddocks, which are connected by lanes to a centrally located milking barn (Figure 2.1). The dairy uses an automatic milking system (AMS), equipped with

two single-stall A3 Lely Astronaut robotic milkers (Lely Industries, N.V., Maassluis, Netherlands). The KBS herd was transitioned from a conventional, confinement system to an AMS in 2009, and to a pasture-based system in 2010. The animals are rotationally grazed for 7 to 8 months of the year, and are fed total mixed ration (TMR) and concentrate, and housed in a free-stall barn during the non-grazing months. The split-barn design, with two herds, is conducive to experimental comparisons of various dairy management strategies.

The KBS pasture includes two diversity treatments of contrasting species composition, seasonality, forage growth, and quality, which were seeded in adjacent 1 ha strips at varying distances from the dairy barn. The high diversity paddocks were seeded in 2008 and include red clover (*Trifolium pratense*), white clover (*Trifolium repens*), alfalfa (*Medicago sativa*), orchard grass (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*). The low diversity paddocks were seeded in 2010, and contain white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*). Both pasture diversity treatments were seeded with equal parts grass and legume.

Average temperature during the study was 18.2 °C, and average precipitation was 4.1 mm/day. Climate data were collected at the KBS Long-Term Ecological Research (LTER) weather station, less than 1 km from the experimental site.

Figure 2.1. The Kellogg Biological Station (KBS) pasture dairy. Paddocks used in this study are highlighted with 2 colors of green, denoting 2 forage species mixtures. A sand laneway leads to a centrally located milking barn. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

Experimental design

To determine the effects of offering multiple pasture diversity treatments (patch heterogeneity), we applied 2 x 2 factorial arrangement of alternating (both species mixtures) and consistent (a single species mixture) pasture rotation treatments to two groups of cows in a complete crossover design. Treatments were replicated across 2 periods of 16 days, separated by a 3-day washout period. All data for this study were collected between 15 May and 18 June 2011.

Animals and Grazing Management

Two herds of 48 (±4 on any given day) United States Holstein (USH) cows were used in the study. Herds were rotationally grazed, with two fresh pasture breaks per day at opposite locations (north and south) of the farm (Figure 2.1). This controlled traffic system was used to entice visitations to the AMS milking barn at least twice per day. Fresh pasture breaks were offered at 0500 h and 1300 h, to mimic typical am and pm grazing habits (Orr et al., 2001). Each pasture break consisted of a 0.5 ha subplot of the 1 ha paddock strips, with each subplot, or pasture break, defined as a patch. Polywire fence was used to subdivide paddocks. Target feed allocation per animal was ~20 kg DM/day, comprised of ~6 kg ground corn concentrate, fed through automatic Cosmix corn feeders (Lely Industries, N.V., Maassluis, Netherlands) and as a pellet reward in the AMS. The rest of the diet was supplied by pasture. Lely Grazeway gates (Lely Industries, N.V., Maassluis, Netherlands) regulated exit from the milking barn. Exit permission was granted based on either a minimum milk yield of 9.1 kg/milking or a minimum milking interval. Expected milking intervals varied with on a given animal's number of days into lactation (days in milk; DIM), based on a maximum and minimum number of milkings. The milking setting used was maximum and minimum number of milkings of 5 and 4 for cows < 30 DIM, 4 and 3 for cows between 31 DIM and 30 days prior to "dry off" (i.e. end of lactation), and, 3 and 2 for cows within 29 days of dry off, respectively. Dry off occurred when cows reached 252 days of gestation.

Animal Sampling

In order to determine whether distance to the pasture affected movement behaviors and milk production, we examined its direct effect on several variables: bout frequency, patch residence time, milking frequency, and milk yield. From each herd, a subset of 14 cows balanced for parity (1.75 ±0.22), DIM (138 ±13), body weight (BW; 522 ±15 kg), and previous milk yield (23.7 ±0.9 kg) were used as test subjects. All test animals were successfully bred prior to the study. Within each subset of 14 cows, 6 individuals were fitted with Global Positioning System (GPS) collars equipped with temperature, head position, Y-axis, and X-axis sensors (Lotek Wireless Inc., Newmarket, ON, Canada). The GPS units took a location fix every 5 minutes. Prior to analysis, GPS fixes were differentially corrected with N4 v.1.1895 software (Lotek Engineering Inc., Newmarket, ON, Canada) based on GPS data from the National Geodetic Survey continuously operating reference station at Plainwell, Michigan (MIPW, www.ngs.noaa.gov/CORS/). Differentially corrected location points were then used to determine horizontal distance walked, duration and frequency of feeding bouts, as well as patch residence time relative to distance from the barn (ArcGIS 9.3, Environmental Systems Research Inc., Redlands, CA, USA). For the purpose of this study, a "feeding bout" was defined as series of consecutive location fixes within a given paddock. A return to the barn, indicated by a series of fixes in the laneway and milking barn, concluded a feeding bout, and any subsequent fixes within a paddock were defined as a new feeding bout. "Patch residence time" (or "bout length") was defined as the time from the first location fix occurring within a paddock to the final consecutive location fix occurring within that paddock.

Lely T4C software (Lely Industries, N.V., Maassluis, Netherlands) was used to retrieve average milk yield and milking frequency data collected by the AMS on a daily basis. The AMS

units were also programmed to collect milk samples from experimental cows on days 8 and 16 of each experimental period. Milk samples were analyzed by Universal Lab Services (Northstar Cooperative, Inc., DHIA, East Lansing, Michigan) for somatic cell count (SCC) and solids, including milk fat, milk protein, and lactose content. Occupancy time (%), number of milkings and milk yield per AMS were also retrieved from the AMS using the T4C software.

Pasture Sampling

Pre- and post-grazing pasture height and herbage mass in both of the pasture types were determined weekly, using a laser-based rapid pasture meter (C-Dax Agricultural Solutions, Ltd., Palmerston North, NZ), and daily, using a rising plate meter (RPM; F400 plate meter, Farmworks, Palmerson North, NZ). A total of 30 RPM readings per paddock were used to estimate the pre- and post- grazing biomass on any given day. Average intake rate (kgDM/ha) was determined with the agronomic difference method (Coates and Penning, 2000) from pre- and post-grazing forage biomass estimates. Additionally, hand-clipped, 0.5 m^2 quadrant forage samples were collected (as described by Mannetje, 2000) every 4 days to determine quality of forage offered, rejected, and consumed. Samples were dried in a forced-air oven at 60°C, ground through a 1-mm screen (Christy Mill, Christy Turner Ltd., Suffolk, UK), and composited by paddock for each sampling day. Forage samples were then analyzed for crude protein (CP) with an ECS 4010 CN combustion analyzer (Costech Analytical Technologies Inc., Valencia, CA) and neutral detergent fiber (NDF) with an Ankom 200 analyzer (Ankom Technology Corp., Fairport, NY). Plant cover and botanical composition were determined following the line point intercept method (Mannetje and Jones, 2000). Physiological development stages of key grass

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(Moore et al., 1991) and legume (Kalu and Fick, 1981) species were also determined every 4 days.

Statistical Analyses

All analyses were performed using SAS v.9.3 (Statistical Analysis Software, Cary, NC). When appropriate, results are reported as least square means ± standard error of the mean (SE). Results were considered statistically significant at a probability of $\alpha < 0.05$.

Artifacts

Due to the fact that the cows were adapted to receiving a fresh pasture break at approximately 0500h and 1300h each day, and often spent the night in the paddock opened at 1300h, a "day" was defined as the 24-hour period from 0500h on a given day to 0459h on the following day. Measurements of grazing bout frequency, total distance traveled, and average patch residence times were recorded for each day. On a day-by-day basis, some animals extended their stays in the pasture allocation from the previous day beyond 0500h. To avoid counting this time as a new feeding bout, GPS fixes were assessed by day from the first fix located within the milking barn after 0459h to the first fix within the barn after 0459h on the following day.

During the first period of the crossover study, 3 animals lost their GPS collars. Collars were recovered and reattached within 1 to 3 days. For these particular individuals, data from the days on which the collars were lost and reattached, as well as any intervening days, were excluded from analysis. In total, 4 days each were excluded for the first 2 individuals that lost their collars, and 2 days were excluded for the third individual. Collar attachment methods were

revised to prevent this problem during the second period of the study. Finally, a fourth experimental animal was separated into a holding pen for part of 1 day, due to a computer error. For this animal, data from this date were also excluded from analysis.

Pasture composition

Data from hand-clipped forage samples throughout the study were used to compare the two pasture species mixtures. The t-test procedure was used to compare dry matter (DM), height, plant cover, CP, NDF, and grass-legume ratios between the two pasture types offered to the cows. Data from 100 hand-clipped forage samples were analyzed (55 from the 5-species mixture, and 45 from the 2-species mixture). For analysis of DM only, 10 samples from each species mixture were excluded from analysis due to unavailable data.

Data from RPM measurements were used in the t-test procedure to compare DM offered and DM intake between the two species mixtures. A total of 59 RPM measurements (28 from the 5-species mixture, and 31 from the 2-species mixture) were used to compare DM offered. For analysis of residual and DM intake, 1 RPM sample from each species mixture was excluded from analysis due to unavailable data.

Distance, Movement Behavior, and Milk Yield

Analyses of the effects of distance on behavior (bout frequency, patch residence time) and milking variables (milking frequency, milk yield) were conducted using the REG procedure. Since paddocks were grazed multiple times, and individual animal movements to and from paddocks may not have been independent due to the herding nature of cattle, the MEANS procedure was used to aggregate data across subjects prior to analysis. Data from one paddock

were excluded because the sward was overly mature, and the herdswoman noted that most of the herd refused to graze at that location.

We developed two structural equation models (SEM; Figures 2.2, 2.3) to separately examine the direct and indirect effects of environmental and internal cow variables on behavior and milk yield. The SEM analyses were conducted using the CALIS procedure (Hartmann, 1992). In the first model, we estimated standardized regression coefficients (r) for the direct and indirect effect of pasture distance on feeding bout frequency, patch residence time, milking frequency, and milk yield (Figure 2.2). A Chi-square analysis was used to test the goodness of fit by model. Pearson correlation coefficients were also used to assess the strength of association between variables. In a second model, standardized regression coefficients (r) for the direct and indirect effect of pellet supplementation in the AMS, days in milk, and visitations to the AMS on milking frequency and milk production were determined following same procedures (Figure 2.3).
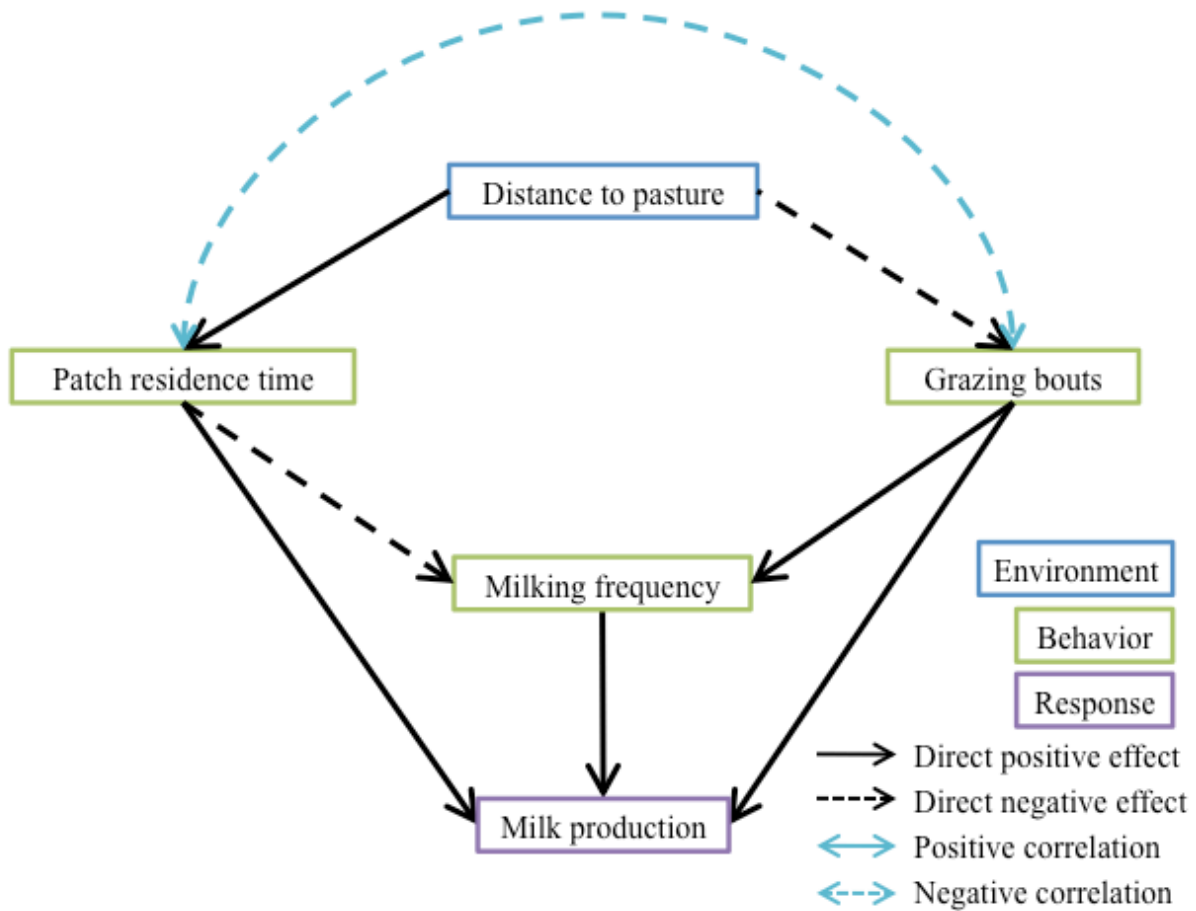
Figure 2.2. Proposed structural equation model of relationships between the variables of distance to pasture, cattle grazing behaviors, and milk production in a pasture dairy system with voluntary milking.
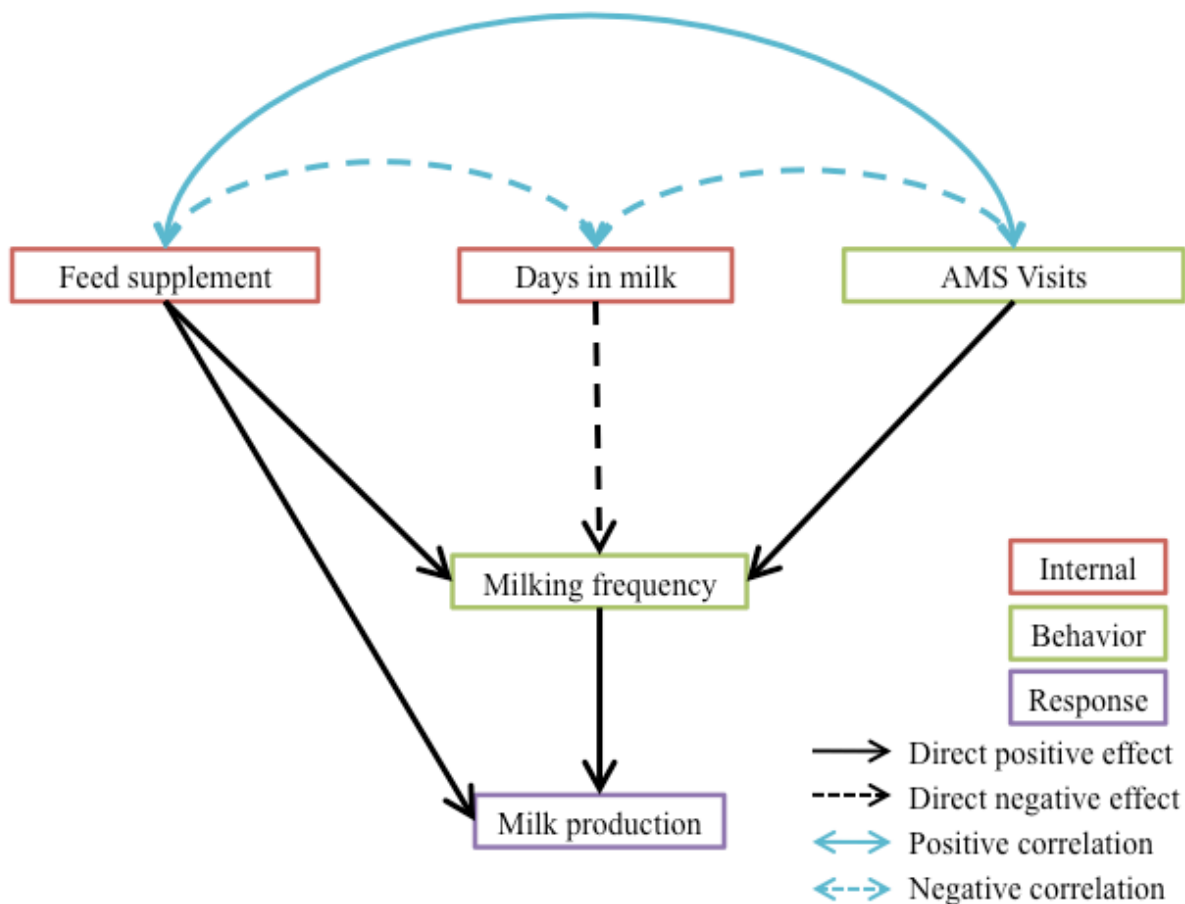
Figure 2.3. Proposed structural equation model of relationships between the variables of lactation state, cattle grazing behaviors, and milk production in a pasture dairy system with voluntary milking.

Patch Heterogeneity

Analysis of variance by the least-squares method was conducted with the MIXED procedure, using the Kenward & Roger (1997) method for degrees of freedom to compare the effects of cow, pasture rotation sequence, and crossover period on movement behaviors (bout frequency, patch residence, and milking frequency) and production (milk yield, AMS occupancy, and milk quality) in the following model:

$$Y_{ijk} = \mu + \alpha_i + \beta_i + \gamma_k + \beta_i * \gamma_j + \varepsilon_{ijk}$$

Where:

Y_{ijk} = movement behavior or production variable of interest;

μ = overall mean;

α_i = random effect of cow (i = 12 GPS-collared cows);

β_i = pasture rotation sequence (j = 2 rotation sequences, either alternating or consistent);

γ_k = period (k = 2 periods); and

ε_{ijk} = residual error.

RESULTS

Pasture composition

Between grazed patches of the two pasture species mixtures, there was a significant difference for all nutritional and compositional characteristics, as well as utilization by the cows (Table 2.1). Distance to grazed patches ranged between 101 and 540 m. No difference ($P = 0.88$) was detected in average distance to patches between the two pasture species mixtures. Average distance to grazed pastures was 313 ± 23 m.

Table 2.1. Characteristics of 5-species and 2-species pasture mixtures (±SE). Pasture mixtures were rotationally grazed by lactating dairy cows in a voluntary automated milking system. Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture). Height, plant cover, CP, NDF, and DM content were determined from hand clipped forage samples (N = 100). DM offered, residual and utilization were determined from rising plate meter measurements (N = 59). Intake per cow was estimated by dividing intake per day by the number of cows in the herd.

	Pasture Mixture		*P* value
	5-species	2-species	
Height (cm)	51.96 (±2.01)	32.11 (±1.06)	< 0.001
Plant cover (%)	50.36 (±1.8)	67.56 (±2.16)	< 0.001
CP (%)	14.24 (±0.31)	17.92 (±0.41)	< 0.001
NDF (%)	58.57 (±0.95)	46.28 (±0.72)	< 0.001
DM (%)	16.95 (±0.55)	12.88 (±0.59)	< 0.001
Grass (%) : Legume (%)	51 : 49 (±3.6)	28 : 72 (±3.1)	< 0.001
DM offered (kg/ha)	3304.6 (±118.59)	1914.02 (±65.17)	< 0.001
DM residual (kg/ha)	1714.86 (±95.59)	1029.23 (±46.3)	< 0.001
DM utilization (kg/ha)	1581.04 (±131.53)	876.98 (±69.75)	< 0.001
DM intake (kg/day)	837.59 (±103.99)	488.31 (±40.66)	< 0.004
DM intake per cow (kg/day)	17.87 (±2.22)	10.17 (±0.84)	< 0.003

Distance to pasture

Movement Behavior and Milk Yield

Distance to the pasture significantly increased ($P = 0.02$) patch residence time (Figure 2.4a) and decreased ($P = 0.002$) bout frequency (Figure 2.4b). Distance to the pasture alone had no effect ($P = 0.52$) on milk yield (Figure 2.5a), however, we did find that overall traveling distance walked by an animal (distance to the pasture x number of grazing bouts/day) decreased ($P = 0.009$) production (Figure 2.5b). We also found that distance to the pasture had no direct effect ($P = 0.2$) on milking frequency. Across distances tested, average milking frequency was 2.24 ± 0.09 milkings/day.
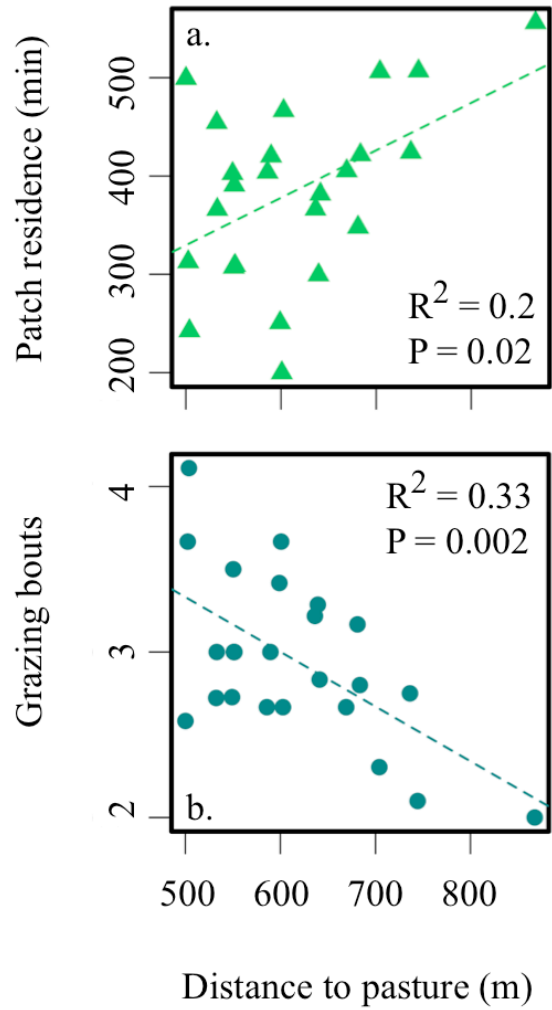
Figure 2.4. Effects of distance from barn to pasture on a) patch residence time and b) number of grazing bouts per day exhibited by cows in a pasture dairy system with voluntary milking. N = 24.
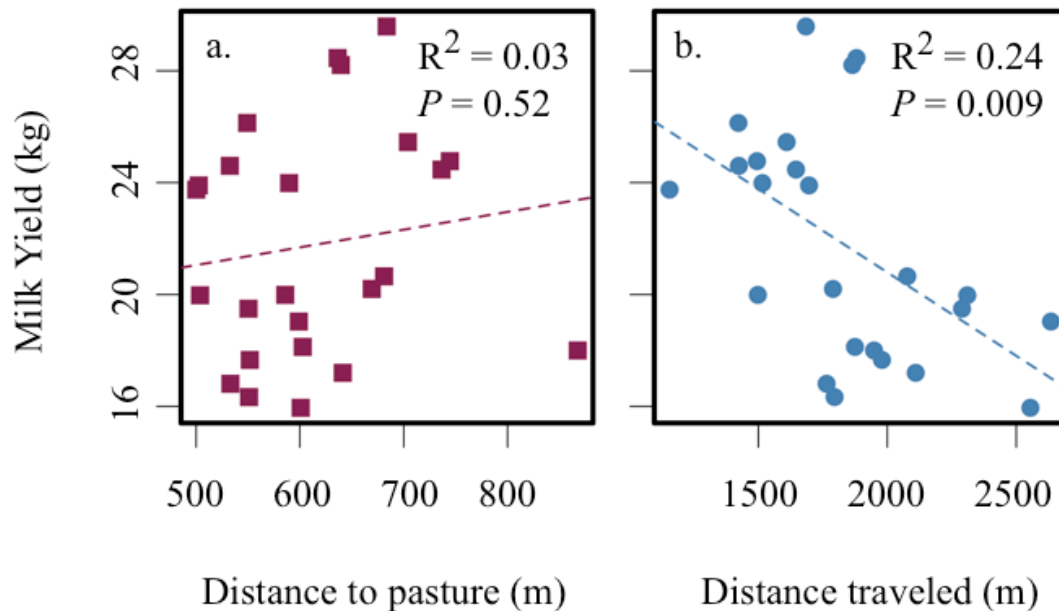
Figure 2.5. Effect of a) distance to pasture on daily milk yield, and b) overall distance traveled (distance to pasture x number of grazing bouts) on daily milk yield of cows in a pasture dairy system with voluntary milking. N = 24.

The first structural equation model detected several significant covariate relationships between distance, movement behavior variables, and milk yield (Figure 2.6). We detected a strong negative correlation between grazing bouts and patch residence (r = -0.79; $P < 0.001$). Number of grazing bouts decreased (r = -0.20, $P < 0.001$), while patch residence time increased (r = 0.16, $P < 0.001$) with the increase in distance between patches. By altering number of grazing bouts and patch residence time, distance also indirectly impacted milking frequency and milk yield. Increases in grazing bouts increased both milking frequency (r = 0.36, $P < 0.001$) and milk yield (r = 0.22, $P < 0.001$), but increases in patch residence time reduced milking frequency (r = -0.25, $P < 0.001$) and increased milk yield (r = 0.16, $P < 0.01$).
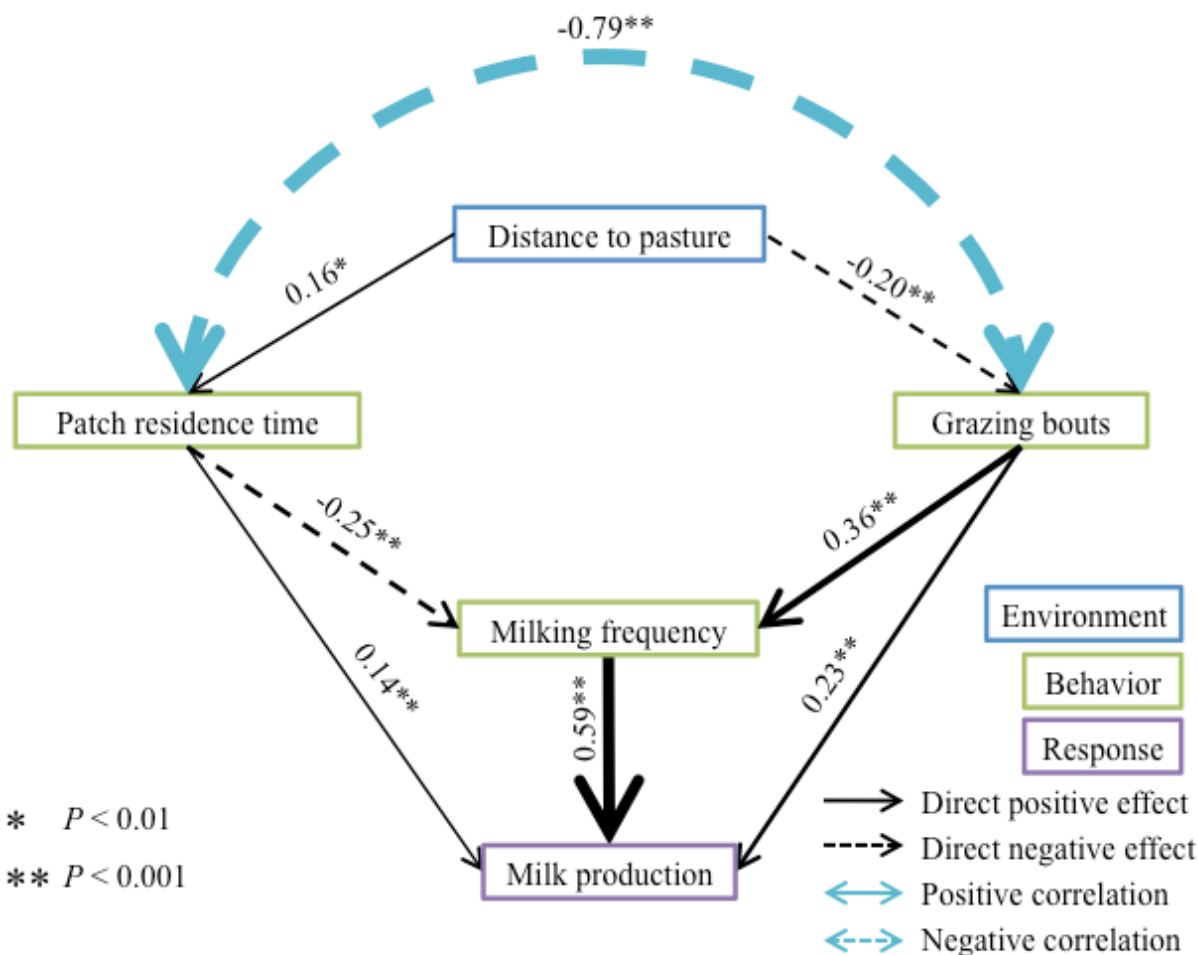
Figure 2.6. Structural equation model showing standardized regression coefficients for the direct and indirect effects of pasture distance on dairy cow grazing behaviors, milking frequency, and milk production in a pasture-based system with voluntary milking. Arrow weight indicates strength of relationships between variables. N = 373.

The second structural equation model detected some significant covariate relationships between DIM, feed supplement quantity, AMS use variables, and milk yield (Figure 2.7). Milking frequency increased both with feed supplement provided by the AMS (r = 0.68, $P <$ 0.001) and frequency of AMS visits (r = 0.38, $P <$ 0.001). We detected a negative correlation between DIM and supplement intake in the AMS (Figure 2.7). Conversely, we found a positive correlation between supplement intake and AMS visits (Figure 2.7). However, DIM had no significant impact on milking frequency (r = -0.005, $P >$ 0.05). In turn, milking frequency had a

positive influence on milk yield (r = 0.14, $P < 0.01$). Amount of feed supplement provided by the AMS increased milk yield indirectly, by increasing milking frequency, but supplement also had a strong direct effect on yield (r = 0.66, $P < 0.001$).
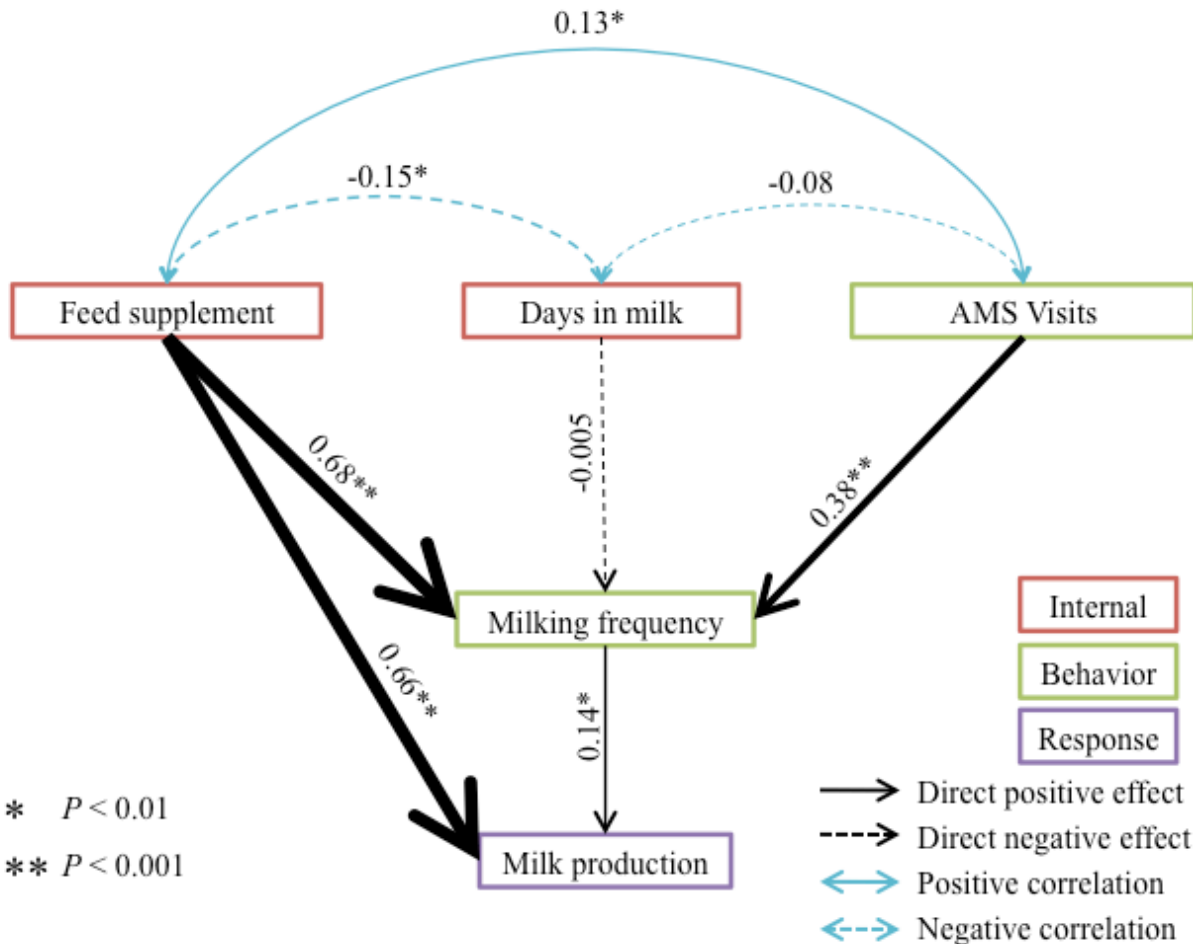
Figure 2.7. Structural equation model showing standardized regression coefficients for the direct and indirect effects of dairy cow lactation state, feed supplement and AMS visits on milking frequency and production in a pasture-based system using voluntary milking. Arrow weight indicates strength of relationships between variables. N = 384.

Grazing Rotation Sequence

Movement Behavior, Milk Yield and Milk Quality

As shown in Table 2.2, pasture rotation sequence had no effect on daily milk yield (μ = 22.4 kg/cow, $F_{1,52} = 0$, $P < 0.99$), number of milkings (μ = 2.24, $F_{1,52} = 0.66$, $P < 0.42$), patch

residence time ($\mu = 378.5$ min, $F_{1,20} = 0.01$, $P < 0.93$), or number of grazing bouts ($\mu = 3$, $F_{1,20} = 0$, $P < 0.99$).

Table 2.2. Grazing behavior and milk production variables ($\pm$ SE) of dairy cows with significance ($P < 0.05$) for difference between two pasture rotation sequences: Alternating grazing allocations between pasture mixtures of different composition, or consistently grazing animals on pasture mixtures of the same composition. For time on pasture, grazing bouts, and patch residence, N = 12, for all other variables, N = 28.

	Pasture Rotation		*P* value
	Alternating species	Consistent species	
Total Time on Pasture (min)	962.16 ($\pm$17.76)	940.27 ($\pm$17.68)	0.393
Grazing bouts/day	3.00 ($\pm$0.26)	3.00 ($\pm$0.26)	0.991
Patch Residence (min)	376.22 ($\pm$35.88)	381.19 ($\pm$35.86)	0.923
Milkings/day	2.19 ($\pm$0.09)	2.29 ($\pm$0.09)	0.421
Milk Yield (kg/milking)	10.82 ($\pm$0.41)	10.52 ($\pm$0.41)	0.603
Milk Yield (kg/day)	22.4 ($\pm$1.00)	22.4 ($\pm$1.00)	0.999

Pasture rotation sequence had no effect ($P > 0.05$) on SCC, solids, protein content, or lactose content (Table 2.3). However, fat content of milk produced by cows grazing an alternating species sequence was significantly greater ($P = 0.035$) than that of cows consistently grazed on the same species mixtures (Table 2.3).

Table 2.3. Milk quality variables ($\pm$SE) with significance ($P < 0.05$) for difference between dairy cows grazed on two pasture rotation sequences: Alternating grazing allocations between pasture mixtures of different composition, or consistently grazing animals on pasture mixtures of the same composition. N = 28.

	Pasture Rotation		*P* value
	Alternating species	Consistent species	
Fat (%)	3.63 ($\pm$0.19)	3.06 ($\pm$0.19)	0.035
Protein (%)	2.73 ($\pm$0.05)	2.79 ($\pm$0.05)	0.38
Lactose (%)	4.78 ($\pm$0.05)	4.76 ($\pm$0.05)	0.81
Solids (%)	5.67 ($\pm$0.06)	5.66 ($\pm$0.06)	0.83
SCC (cells x 10^3/mL)	160.6 ($\pm$72.4)	172.8 ($\pm$72.4)	0.91

AMS Performance

Pasture rotation sequence had no effect on overall use of the AMS by the herd (Table 2.4).

Table 2.4. Daily Automated Milking System (AMS) performance variables (±SE) with significance ($P < 0.05$) for difference between herds of 48 (±4) dairy cows grazed on two pasture rotation sequences: Alternating grazing allocations between pasture mixtures of different composition, or consistently grazing animals on pasture mixtures of the same composition.

	Pasture Rotation		*P* value
	Alternating species	Consistent species	
Milkings	105.75 (±9.05)	107.25 (±9.05)	0.926
Milk Yield (kg)	1007.95 (±84.4)	1014.7 (±84.4)	0.964
Occupancy (%)	55.94 (±1.49)	55.49 (±1.49)	0.867

DISCUSSION

AMS are becoming increasingly popular in North America, largely for their potential to reduce labor costs and increase milk production (Hogeveen et al., 2004; de Koning and Rodenburg, 2004). However, implementing AMS in pasture-based systems has not always resulted in increased milk production, and may result in decreased milking frequency as cows spend more time on pasture (Ketelaar-de Lauwere et al., 1999; Utsumi, 2011). Encouraging voluntary movement of cows is key to maintaining efficiency in systems that integrate these two management practices (Rossing et al., 1997; de Koning and Rodenburg, 2004). We examined whether, at the whole system scale, dairy cows would conform to theoretical predictions of animal foraging behavior and movement.

As a means of balancing energy budget, animals tend to forage in patches of food items for a length of time that is roughly proportional to the energy they expend to travel between those patches (MacArthur and Pianka, 1966; Charnov, 1976). This principle has been empirically demonstrated in a variety of wild ruminants (Kotler et al., 1994; Shipley and Spalinger, 1995; Searle et al., 2005), but only rarely in dairy cattle (Utsumi et al., 2009). Some evidence also suggests that variety in forage types may motivate movements in animals (Villalba and Provenza, 1999; Marotti et al., 2002a; Rutter, 2006). Large herbivores in particular, when

consuming large quantities of plant biomass, are motivated to seek novel food items to offset buildup of toxins of secondary metabolites (Forbes, 2000; Bailey and Provenza, 2008). Most previous studies have only tested animal responses to variety and distance at a small scale (patch sizes consisting of a few bites), and it is unclear whether these principles hold for large-scale patches. In this study, we examined movement behaviors in response to both pasture distance from the barn and pasture heterogeneity. Both of these factors may play a role in motivating animal movements, and may therefore have an impact on the success of integrating AMS with grazing.

Previously, distance to the pasture had no effect on voluntary milking frequency of animals (Ketelaar-de Laurwere et al., 2000). Our study showed a similar trend. We did, however, find that distance to the pasture affects the length and number of grazing bouts, and in doing so, has an indirect effect on milking frequency and milk yield. Our results suggest a trade-off between grazing bout length and frequency, as both of these factors interestingly had a direct positive effect on milk yield. As pasture visitation frequency increased, by definition the number of return visits to the milking barn also increased, resulting in a greater overall likelihood of voluntary milking events. Conversely, as cows took fewer and longer bouts, voluntary milking frequency decreased. Despite this indirect negative effect on milk yield, due to decreased milking frequency, bout length also had a positive effect on yield directly. It is possible that increased bout length is indicative of longer grazing time and greater energy intake overall, which would likely translate to greater milk output. We also found that bout frequency had a positive effect on milk yield beyond its influence on milking frequency. It is possible that a greater number of bouts is indicative of more time spent on pasture, which again would suggest greater energy intake by the animal. Although measuring precise energy intake per individual

was beyond the scope of this study, the variables of bout length and frequency both appear to be proxies for energy intake in their direct effects on yield. It will be important, however, to determine if energy intake is a hidden variable linking bout length and milk yield, as well as bout frequency and milk yield. We also found that the amount of supplement provided by the AMS is an important driver of both milking frequency and milk yield, which was expected, as supplement is meant to be both a motivation for voluntary milkings, as well as a source of energy (Garcia and Fulkerson, 2005).

Contrary to our expectation, and to previous studies (Rutter, 2006; Champion et al., 2004), animals did not increase movements when pasture availability alternated between contrasting patches. Previous studies had only explored the response of animal movements between adjacent monocultures. Our goal was to test for this response with mixed pastures, which are typically resilient for a longer portion of the growing season, and more closely match the plant communities of typical pasture-based farms. Ruminants do select for variety in their diet on a small scale (Champion et al., 2004), but it could be that broad-scale movements (across patches) are more strongly motivated by monocultures, or by abiotic factors such as temperature or distance between patches (Senft et al., 1987; Bailey et al., 1996). Although the two pasture mixtures included different and contrasting species, each mixture included both legume and grass species. It is possible that animals were selecting for variety on a more localized scale (i.e. individual bites), so movement between pastures was not necessary to satisfy nutritional requirements. Since variety in the pasture rotation sequence had no effect on animal movements, it was not surprising that it did not alter their use of the AMS. Milk quality was also similar between both rotation sequences, although milkfat content was greater when cows grazed the alternating pasture sequence. It is unclear why fat was the only variable that differed between the

two treatments. It will be interesting to explore further options for motivating visits to the AMS in a pasture-based system. Perhaps different plant species mixtures or supplements within the pasture would be more effective means of encouraging movement.

CONCLUSIONS

Broad-scale animal responses to the pasture environment play a crucial role in the success of AMS on pasture dairies. Maintaining high voluntary milking frequency throughout the grazing season is important to ensure maximum production. Requiring too much movement effort between pasture allocations and the AMS, however, could have an energetic cost, negatively impacting milk yield. Animals responded to distance between patches, but showed no evident response to patch heterogeneity at a broad scale, conforming to optimal foraging predictions, but not to the satiety hypothesis. Further research will be necessary to improve pasture and AMS management strategies that motivate movement while maintaining a high conversion rate of forage to milk.

CHAPTER 3

DO COWS EXHIBIT TEMPORAL SELECTIVITY FOR FORAGE SPECIES IN A FREE-TRAFFIC PASTURE SYSTEM?

Abstract

Strategic management of cow traffic is central to the success of automated milking systems (AMS), particularly on pasture-based dairies. Spatial and temporal placement of desirable forage items may be used to entice voluntary milkings in the AMS. Due to strong diurnal fluctuations in water-soluble carbohydrate (WSC) content of certain plant species, cows often exhibit temporal preference for particular plants. Managing pasture rotations based on forage preferences may be one strategy for enticing AMS visits. We applied a two phase study, consisting of a preliminary preference trial, and a subsequent crossover study comparing temporally alternating pasture rotation sequences to two groups of 48 ($\pm$3) dairy cows. We used a pasture system with two contrasting plant species mixtures, one containing perennial ryegrass and white clover (2-species mix), and the other containing orchard grass, tall fescue, white clover, red clover, and alfalfa (5-species mix). Based on previous research, cows were expected to favor the 2-species mix, particularly during evening hours. During the preference trial, cows were offered free choice between adjacent swards of each mixture to test for temporal preference. During the grazing rotation sequence study, cows received 2 pasture breaks, one of each mixture, per day. Contrary to expectation, cows preferred ($P < 0.05$) the 5-species pasture mixture regardless of time of day. During the rotation sequence, cows allocated more time ($P < 0.05$) toward grazing during PM hours, regardless of species mix. This study was among the first to examine diurnal preference between contrasting species mixtures at the more broad spatial scale of paddocks. Our findings suggest that diurnal foraging preferences may only apply at smaller spatial scales.

INTRODUCTION

Background

In the current economic climate, dairy farmers face a choice between increasing their production with greater concentrate feed input, or decreasing expenses by relying primarily on low cost pasture-based feeding systems. Although pasture-based systems often reduce production as well as cost, recent scientific advancements may improve production in these low-input systems (Garcia and Fulkerson, 2005). Automated milking technology is becoming increasingly popular, for its potential to reduce labor costs and increase milk production (de Koning and Rodenburg, 2004; de Koning, 2010, 2011). While production can be improved with this new milking technology, modifying herd diets is also valuable for increasing yield. Forage crop breeders are developing high-sugar grass cultivars with the goal of increasing production by grass-fed animals (Miller et al., 2001; Downing and Gamroth, 2007).

High-sugar (HS) grasses, such as perennial ryegrass (*Lolium perenne*), are becoming more popular on pasture-based dairy farms, particularly in New Zealand and the United Kingdom. These grasses are desirable in part for their high water-soluble carbohydrate (WSC) and non-structural carbohydrate (NSC) content, which yields greater digestibility, and in turn, increased milk production (Downing and Gamroth, 2007). Aside from their potential to improve production, HS grass diets may increase milk protein content (Moorby et al., 2006), and may also alter nutrient cycling by reducing excess nitrogen excretion into the environment. When cows consume HS grasses, a greater proportion of dietary N is secreted in milk, rather than urine (Miller et al., 2001). Swards containing plant species with high WSC concentrations are nutritionally superior to those with low WSC, and dairy cows consistently show preference for plants with high WSC. Evaluation of preference choices among 14 forage species revealed that

dairy cows consistently preferred perennial ryegrass over lower WSC grasses such as tall fescue and orchard grass (Horadagoda et al., 2009). In the same study, cows also preferred white clover over other legumes such as alfalfa and red clover. Between monocultures of perennial ryegrass and white clover, dairy cows and sheep show a 70% partial preference for clover, while still including perennial ryegrass (Marotti et al., 2002a; Rutter, 2006), but a system containing multiple grass species may yield a different response. If a preference between HS and non-HS grasses does exist, the degree of preference may vary temporally, since low temperatures further increase WSC concentration in HS cultivars (Parsons et al., 2004). Concentrations of NSC also tend to spike during the cooler evening hours in both perennial ryegrass (Taweel et al., 2006) and orchard grass (Griggs et al., 2007), A temporal preference for or against HS grasses would have important implications for managers seeking new strategies to manipulate animal movements throughout the pasture system.

A major challenge in integrating automated milking systems (AMS) with pasture-based farming is providing motivation for the animals to voluntarily visit the milking unit (Garcia and Fulkerson, 2005). Although AMS has the potential to increase milk yield (de Koning and Rodenburg, 2004), pasture-based farms that adopt this technology often see a decrease in production as animals visit the milking unit less frequently (Ketelaar-de Lauwere et al., 1999; Utsumi, 2011). Food incentives, including multiple pasture breaks per day (Davis et al., 2007; Lyons, 2011), and strategically placed concentrate rewards (Jago et al., 2002), are useful for encouraging AMS visits and increasing production. Differential behavior responses to swards containing plants with contrasting WSC concentrations may offer another option for encouraging AMS visits with food-based incentives.

Objectives

This study had two main objectives. Our first objective was to determine whether cows exhibit preference for a given pasture species mixture, and whether this preference varies with time of day. We expected cows to favor a pasture mixture containing perennial ryegrass and white clover during the evening grazing bout, while selecting against this mixture during the morning grazing bout. Our second objective was to determine whether cow movement and milk yield are affected by the order in which cows graze two compositionally distinct swards over the course of a day, including one sward containing perennial ryegrass and white clover.

MATERIALS AND METHODS

Study Site

The study was conducted at the W.K. Kellogg Biological Station (KBS) Dairy in Hickory Corners, Michigan. Prior to the start of this study, protocols were reviewed and approved by the MSU Institutional Animal Care and Use Committee (IACUC). During the study period, the lactating herd included 96 (±2 on any given day) Holstein-Friesian cattle. The farm has 64 ha of pasture, divided into 8 blocks of paddocks, which are connected by a sand laneway to a centrally located milking barn (Figure 3.1). The dairy uses an automatic milking system (AMS), equipped with two single-stall A3 Lely Astronaut robotic milkers (Lely Industries, N.V., Maassluis, Netherlands). The KBS herd was transitioned from a conventional, confinement system to an AMS in 2009, and to a pasture-based system in 2010. The animals are rotationally grazed for seven to eight months of the year, and are fed total mixed ration (TMR) and concentrate, and housed in a free-stall barn during the winter. Lely Grazeway exit gates (Lely Industries, N.V., Maassluis, Netherlands) regulate movement from the barn to the pasture. The split-barn design,

with two herds, is conducive to experimental comparisons of various dairy management strategies.

The KBS pasture includes two diversity treatments of contrasting species composition, seasonality, forage growth, and quality, which were seeded in adjacent 1 ha strips at varying distances from the dairy barn. The high diversity paddocks were seeded in 2008 and include red clover (*Trifolium pratense*), white clover (*Trifolium repens*), alfalfa (*Medicago sativa*), orchard grass (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*). The low diversity paddocks were seeded in 2010, and contain white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*). Both pasture types were seeded with equal parts grass and legume.

Average temperature during the study was 22.3 °C, and average precipitation was 2.6 mm/day. Climate data were collected at the KBS Long-Term Ecological Research (LTER) weather station, less than 1 km from the experimental site.

Figure 3.1. The Kellogg Biological Station (KBS) pasture dairy. Paddocks used in this study are highlighted with 2 colors of green, denoting 2 species mixtures. A sand laneway leads to a centrally located milking barn.

Experimental design

Two experimental phases were used to complete the two main objectives of the study: 1) the test of diurnal preferences of dairy cows offered free choice between contrasting pasture mixtures, and, 2) the evaluation of circadian grazing patterns and milk yield by dairy cows when temporal availability of contrasting pasture mixtures was controlled. All data for this study were collected between 18 June and 19 July 2011.

Animals and Grazing Management

Two herds of 48 (±3 on any given day) United States Holstein (USH) cows were used in the study, and were rotationally grazed on pastures based on the needs of each experimental phase (see below). Target feed allocation per animal was ~20 kg dry matter (DM) per day, comprised of ~6 kg ground corn concentrate, fed through automatic Cosmix corn feeders (Lely Industries, N.V., Maassluis, Netherlands) and as a pellet reward in the AMS. The rest of the diet was supplied by pasture. Lely Grazeway gates (Lely Industries, N.V., Maassluis, Netherlands) regulated exit from the milking barn. Exit permission was granted based on either a minimum milk yield of 9.1 kg/milking or a minimum milking interval. Expected milking intervals varied with a given animal's number of days into lactation (days in milk; DIM), based on a maximum and minimum number of milkings. The milking setting used was maximum and minimum number of milkings of 5 and 4 for cows < 30 DIM, 4 and 3 for cows between 31 DIM and 30 days prior to "dry off" (i.e., end of lactation), and, 3 and 2 for cows within 29 days of dry off, respectively. Dry off occurred when cows reached 252 days of gestation.

Animal Sampling

From each herd, a subset of 14 cows balanced for parity (1.93 ±0.26), DIM (163 ±16), body weight (BW; 503 ±18 kg), and previous milk yield (18.9 ±0.9 kg) were used as test subjects. All test animals were successfully bred prior to the study. Within each subset of 14 cows, 6 individuals were fitted with Global Positioning System (GPS) collars (Lotek Wireless Inc., Newmarket, Ontario, Canada). The GPS collars were equipped with temperature, head position, Y-axis, and X-axis sensors and took a location fix every 5 minutes. Prior to analysis, GPS fixes were differentially corrected with N4 v.1.1895 software (Lotek Engineering Inc.,

Newmarket, ON, Canada) based on GPS data from the National Geodetic Survey continuously operating reference station at Plainwell, Michigan (MIPW, www.ngs.noaa.gov/CORS/). Differentially corrected location points were then used to determine horizontal distance walked, duration and frequency of feeding bouts, as well as bout length (ArcGIS 9.3, Environmental Systems Research Inc., Redlands, CA, USA).

Temporal Preference
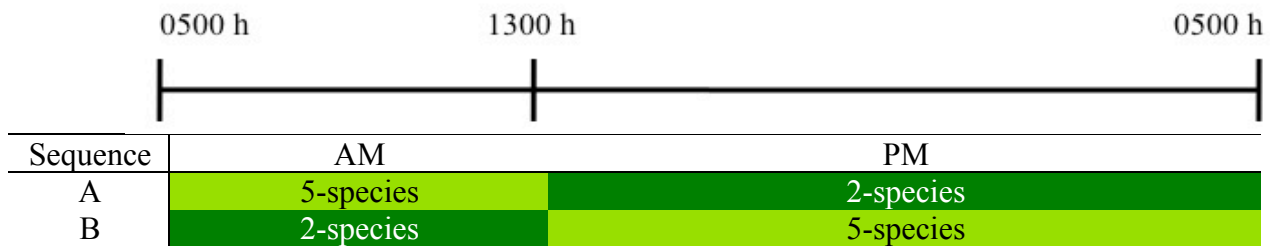
In order to determine whether cows exhibited temporal preferences for different sward mixtures, we conducted two 3-day preference trials in which both herds were offered free choice between adjacent swards of each species mixture. Fresh pasture breaks were offered each day at 0500h and included a 0.66 ha subplot of each plant species mixture. Using GPS location data, we determined overall time spent in each species, and during AM (0000-1200h) and PM (1200-2400h) hours. To account for variability in location accuracy (as described by Ganskopp and Johnson 2007), a 10m buffer was applied to the border between the two species mixtures, and all fixes within this buffer zone were excluded from analysis.

Grazing sequence

To determine any circadian effects of alternating forage sequences, we applied a factorial arrangement of 2 diurnal sequences that alternated between 2 pasture mixtures in a complete crossover design (Table 3.1). Treatments were replicated over 2 periods of 12 days, separated by 3-day washout periods. Herds were rotationally grazed, with two fresh pasture breaks per day at opposite locations (north and south) of the farm (Figure 3.1). This controlled traffic system was used to entice visitations to the AMS milking barn at least twice per day. Fresh pasture breaks

were offered at 0500 h and 1300 h, to mimic typical am and pm grazing habits (Orr et al., 2001).

Each pasture break consisted of a 0.5 ha subplot of the 1 ha paddock strips. Polywire fence was

used to subdivide paddocks.

Table 3.1. Daily timing of fresh pasture breaks in two sequences of alternating pasture mixtures offered to dairy cows in a voluntary automate milking system (AMS). Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture).

	0500 h	1300 h	0500 h
Sequence	AM	PM	
A	5-species	2-species	
B	2-species	5-species	

Using GPS data, we determined frequency and duration of grazing bouts and overall time

spent on pasture (grazing bout frequency x grazing bout length). For the purpose of this study, a

"feeding bout" was defined as series of consecutive location fixes within a given paddock. A

return to the barn, indicated by a series of fixes in the laneway and milking barn, concluded a

feeding bout, and any subsequent fixes within a paddock were defined as a new feeding bout.

"Bout length" was defined as the time from the first location fix occurring within a paddock to

the final consecutive location fix occurring within that paddock.

T4C software (Lely Industries, N.V., Maassluis, Netherlands) was used to retrieve

average milk yield and milking frequency data collected by the AMS on a daily basis. The AMS

units were also programmed to collect milk samples from experimental cows on day 12 of each

experimental period. Milk samples were analyzed by Universal Lab Services (Northstar

Cooperative, Inc., DHIA, East Lansing, Michigan) for somatic cell count (SCC) and solids,

including milk fat, milk protein, and lactose content. Occupancy time (%), number of milkings

and milk yield per AMS were also retrieved from the AMS using the T4C software.

Pasture Sampling

Pre- and post-grazing pasture height and herbage mass in both of the pasture mixtures were determined weekly, using a laser-based rapid pasture meter (C-Dax Agricultural Solutions, Ltd., Palmerston North, NZ), and daily, using a F400 rising plate meter (RPM; Farmworks, Palmerson North, NZ). A total of 30 RPM readings per paddock were used to estimate the pre- and post-grazing biomass on any given day. Average intake rate (kgDM/ha) was determined with the agronomic difference method (Coates and Penning, 2000) from pre- and post-grazing forage biomass estimates. Additionally, hand-clipped, 0.5 m^2 quadrant forage samples were collected (as described by Mannetje, 2000) every 4 days to determine quality of forage offered, rejected, and consumed. Samples were dried in a forced air oven at 60°C, ground through a 1-mm screen (Christy Mill, Christy Turner Ltd., Suffolk, UK), and composited by paddock for each sampling day. Forage samples were then analyzed for crude protein (CP) with an ECS 4010 CN combustion analyzer (Costech Analytical Technologies Inc., Valencia, CA) and neutral detergent fiber (NDF) with an Ankom 200 Fiber Analyzer (Ankom Technology Corp., Fairport, NY). Plant cover and botanical composition were determined following the line point intercept method (Mannetje and Jones, 2000). Physiological development stages of key grass (Moore et al., 1991) and legume (Kalu and Fick, 1981) species were also determined every 4 days.

Statistical Analyses

All analyses were performed using SAS v.9.3 (Statistical Analysis Software, Cary, NC). When appropriate, results are reported as least square means ± standard error of the mean (SE). Results were considered statistically significant at a probability of $\alpha < 0.05$.

Artifacts

Due to the fact that the cows were adapted to receiving a fresh pasture break at approximately 0500h and 1300h each day during the pasture sequence study, and often spent the night in the paddock opened at 1300h, a "day" was defined as the 24-hour period from 0500h on a given day to 0459h on the following day. Measurements of grazing bout frequency, total distance traveled, and average patch residence times were recorded for each day. On a day-by-day basis, some animals extended their stays in the pasture allocation from the previous day beyond 0500h. To avoid counting this time as a new grazing bout, GPS fixes were assessed by day from the first fix located within the milking barn after 0459h to the first fix within the barn after 0459h on the following day.

During the first period of the pasture sequence study, complications with the AMS milk sampling device resulted in the loss of two milk samples. These two samples were excluded from analysis of milk quality.

Temporal Preference

Forage preference indices were calculated based on the proportion of total grazing time spent in the 2-species mixture (see Utsumi et al., 2009; Wallis de Vries et al., 1999). Preference

indices were calculated separately for AM and PM hours, as well as overall preference throughout the day, using the following equation:

$$\frac{T_R / (T_R + T_O)}{B_R / (B_R + B_O)}$$

Where:

R = 2-species pasture mixture, with key species perennial ryegrass;

O = 5-species pasture mixture, with key species orchard grass;

T_i = time spent in pasture mixture i; and

B_i = biomass of pasture mixture i.

Significant preference for the 2-species mixture was indicated by a value greater than 1, and preference for the 5-species mixture was indicated by a value less than 1 (Student's t-test).

Data were analyzed with the MIXED procedure, using a compound symmetry, autoregressive order 1 or unstructured covariance structure where appropriate (Littell et al., 1996), and the Kenward & Roger (1997) method for degrees of freedom, to compare the effects of cow, herd, and trial period on preference for the 2-species mixture in the following model:

$$Y_{ijk} = \mu + \alpha_i + \beta_i + \gamma_k + \beta_i * \gamma_j + \varepsilon_{ijk}$$

Where:

Y_{ijk} = selectivity value (AM, PM, and overall);

μ = overall mean;

α_i = random effect of cow (i = 12 GPS-collared cows);

β_i = herd (j = 2 distinct herds);

γ_k = period (k = 2 periods); and

ε_{ijk} = residual error.

Movement Behaviors and Milk Production

Grazing sequence data were analyzed with the MIXED model procedure, using compound symmetry, autoregressive order 1, or unstructured covariance structure where appropriate (Littell et al., 1996), and the Kenward & Rogers (1997) method for degrees of freedom, to compare the effects of cow, pasture rotation sequence, and crossover period on movement behaviors (bout frequency, bout length) and milk production (milk yield/milking, milk yield/day, milking frequency/day) and milk quality (solids, milk fat, milk protein, SCC), and, AMS performance (milk yield, milkings, occupancy) in the following model:

$Y_{ijk} = \mu + \alpha_i + \beta_i + \gamma_k + \beta_i * \gamma_j + \varepsilon_{ijk}$

Where:

Y_{ijk} = response variable of interest;

μ = overall mean;

α_i = random effect of cow (i = 12 GPS-collared cows);

β_i = pasture rotation sequence (j = 2 rotation sequences, A or B);

γ_k = period (k = 2 periods); and

ε_{ijk} = residual error.

Pasture composition

Forage samples from both the preference trial and the pasture rotation study were used to compare the two pasture species mixtures. The t-test procedure was used to compare means between percent dry matter (DM), sward height, plant cover, CP, NDF, and grass-legume ratios between the two pasture mixtures offered to the cows. For the preference trials, a total of 24 hand-clipped forage samples were analyzed (12 from each species mixture). For the pasture sequence study, data from 84 hand-clipped forage samples were analyzed (45 from the 5-species mixture, and 39 from the 2-species mixture). For analysis of DM only, 6 samples from each pasture mixture were excluded from analysis due to unavailable data.

Data from RPM measurements were used in the t-test procedure to compare DM offered and DM intake between the two pasture mixtures. For the preference trial, a total of 12 RPM measurements (6 from each species mixture) were used to measure DM offered and consumed. For the alternating pasture rotation study, a total of 54 RPM measurements (30 from the 5-species mixture, and 24 from the 2-species mixture) were used to compare DM offered and consumed.

RESULTS

Temporal Preference

Pasture Composition

For swards offered during the preference trial, compositional characteristics tended to differ between the two species mixtures (Table 3.2). Plant cover and protein content were greater in the 2-species mixture, while fiber and dry matter content were greater in the 5-species mixture. The 2-species mixture had a very high proportion of legumes, while the 5-species mixture had equal proportions of grasses and legumes. Sward height, however, did not differ

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between species mixtures. The amount of dry matter offered and consumed were not different

between the two species mixtures.

Table 3.2. Characteristics of 5-species and 2-species pasture mixtures (±SE). Adjacent paddocks of both pasture mixtures were grazed by lactating dairy cows in a voluntary automated milking system, and cows were allowed free movement between the 2 mixtures. Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture). Height, plant cover, CP, NDF, and DM content were determined from hand clipped forage samples (N = 24). DM offered, residual and utilization were determined from rising plate meter measurements (N = 12). Intake per cow was estimated by dividing intake per day by the number of cows in the herd.

	Pasture Mixture		*P* value
	5-species	2-species	
Height (cm)	29.25 (±2.33)	28.92 (±1.81)	0.91
Plant cover (%)	45 (±3.79)	70 (±3.69)	< 0.001
CP (%)	14.33 (±0.77)	18.49 (±0.86)	< 0.002
NDF (%)	55.21 (±0.93)	45.24 (±0.68)	< 0.001
DM (%)	23.59 (±0.97)	16.91 (±0.85)	< 0.001
Grass (%) : Legume (%)	51 : 49 (±9.6)	8 : 92 (±2.8)	< 0.001
DM offered (kg/ha)	1970.15 (±359.7)	1565.2 (±165.86)	0.34
DM residual (kg/ha)	1245.18 (±125.16)	920.4 (±60.22)	0.051
DM intake (kg/ha)	724.97 (±244.04)	644.8 (±122.27)	0.78
DM intake (kg/day)	329.88 (±61.47)	370.72 (±92.38)	0.72
DM intake per cow (kg/day)*	6.77 (±1.18)	7.72 (±1.98)	0.69

Note: Cows were grazing both pasture mixtures in adjacent paddocks, with free movement between the mixtures. Total daily intake per cow is the sum of intake from both species mixtures.

Preference indices

In general, cows spent more time in the 5-species pasture mixture regardless of time of day (Table 3.3), but overall preference for this mixture varied between the two herds ($P <$ 0.0001) and between the two trial periods ($P < 0.008$). Preference during AM hours also differed between herds ($P < 0.0008$), and trial periods ($P < 0.05$). Preference also differed during PM hours between herds ($P < 0.0001$) and periods ($P < 0.005$). In all cases where a preference was detected, cows preferred the 5-species mixture, indicated by preference indices significantly lower than 1 (Table 3.4). Preference for the 5-species mixture was detected in herd 2 and period

2, regardless of time of the day (Table 3.4). Preference for the 5-species mixture was also

detected during AM hours in period 1 (Table 3.4).

Table 3.3. Total time (±SE) that dairy cows spent in 5-species and 2-species pasture mixtures during morning (<1200h) and afternoon (>1200h), when allowed free movement between adjacent paddocks of each species. Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture).

	Time spent in pasture (min / day)		
Pasture mix	AM	PM	Total
5-species	143 (±15)	156 (±14)	299 (±28)
2-species	51 (±7)	91 (±11)	141 (±17)

Table 3.4. Preference indices (±SE) exhibited by dairy cows offered free choice between 5- and 2-species pasture mixtures during AM (0000-1200h) and PM hours (1200-2400h). Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture). Values >1 indicate selection for the 2-species mixture, and values <1 indicate selection against the 2-species mixture (for the 5-species mixture). Significant values ($P < 0.05$) are indicated by asterisks. N = 12.

	Selectivity		
	AM	PM	Overall
Herd			
1	0.90 (±0.09)	1.11 (±0.07)	1.02 (±0.07)
2	0.37 (±0.09)*	0.53 (±0.07)*	0.47 (±0.07)*
Period			
1	0.78 (±0.09)*	0.97 (±0.07)	0.89 (±0.07)
2	0.50 (±0.09)*	0.66 (±0.07)*	0.59 (±0.07)*

Pasture Rotation Sequence

Pasture Composition

Between the two pasture species mixtures, there were some differences in nutritional and

compositional characteristics, as well as utilization by the animals, however, not all

compositional characteristics varied between species mixtures (Table 3.5). The 2-species mixture

had greater plant cover, and lower fiber, however there was no difference in protein or dry matter

content, or overall height of the two species mixtures. Botanical composition differed between

the two mixtures, with the 2-species mixture having a relatively high proportion of legumes, compared with the 5-species mixture, which had nearly equal proportions of grasses and legumes. The 5-species mixture had greater biomass overall, and greater DM intake when residuals were corrected for number of days the sward was grazed.

Table 3.5. Characteristics of 5-species and 2-species pasture mixtures (±SE). Pasture mixtures were rotationally grazed by lactating dairy cows in a voluntary automated milking system. Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture). Height, plant cover, CP, NDF, and DM content were determined from hand clipped forage samples (N = 84). DM offered, residual and utilization were determined from rising plate meter measurements (N = 54). Intake per cow was estimated by dividing intake per day by the number of cows in the herd.

| | Pasture Mixture | | *P* value |
	5-species	2-species	
Height (cm)	27 (±1.15)	26.13 (±1.38)	0.63
Plant cover (%)	51.56 (±1.8)	65.38 (±3.0)	< 0.001
CP (%)	16.8 (±0.34)	15.75 (±0.61)	0.14
NDF (%)	51.42 (±0.65)	45.96 (±1.01)	< 0.001
DM (%)	21.43 (±0.56)	21.25 (±0.75)	0.84
Grass (%) : Legume (%)	52 : 48 (±3.1)	19 : 81 (±4.8)	< 0.001
DM offered (kg/ha)	1959.84 (±78.03)	1528.8 (±63.43)	< 0.001
DM residual (kg/ha)	1327.39 (±55.94)	954.85 (±33.37)	< 0.001
DM intake (kg/ha)	632.45 (±72.34)	573.95 (±59.28)	0.53
DM intake (kg/day)	506.31 (±70.07)	315.95 (±37.06)	< 0.001
DM intake per cow (kg/day)	10.64 (±1.47)	6.68 (±0.79)	< 0.001

Note: Cows were grazing both pasture mixtures, in spatially distinct paddocks over the course of each day. Total daily intake per cow is the sum of intake from both species mixtures.

Temporal Selectivity

Overall, cows spent more time grazing and showed stronger selectivity for both pasture mixtures during the evening hours, even after correcting for the difference in time between AM and PM pasture breaks. During the morning, cows spent more time in the 5-species mixture than in the 2-species mixture, and only exhibited significant selectivity for the 5-species mixture (Table 3.6).

Table 3.6. Total time (±SE) that rotationally grazed dairy cows spent in 5-species and 2-species pasture mixtures during morning (0500-1300h) and afternoon (1300-0500h) grazing bouts, as well as time-corrected selectivity indices (±SE) for each species mixture. Selectivity indices > 1 indicate selectivity for a given species mixture, while selectivity scores < 1 indicate selectivity against that species mixture. Selectivity indices significantly different from 1 are denoted by an asterisk ($P < 0.05$). N = 12.

Pasture mixture	Time on pasture (min)		Selectivity	
	AM	PM	AM	PM
5-species	105 (±9)	642 (±16)	1.37 (±0.1)*	2.03 (±0.1)*
2-species	71 (±9)	657 (±14)	0.97 (±0.1)	2.74 (±0.1)*

Grazing Behavior and Milk Production

Pasture rotation sequence had no effect ($P > 0.05$) on cows' grazing behavior, milking frequency, or milk yield (Table 3.7). Furthermore, rotation sequence also had no effect ($P > 0.05$) on milk fat, milk protein, solids, or SCC (Table 3.7)

Table 3.7. Grazing behavior, milking frequency, milk yield and milk composition (±SE) with significance ($P < 0.05$) for difference between dairy cows grazed on two daily pasture rotation sequences: A 5-species pasture mixture during the morning (0500-1300h) and a 2-species pasture mixture during the afternoon and evening (1300-0500h), "Sequence A," or the reverse, a 2-species pasture mixture during the morning and 5-species during the afternoon and evening, "Sequence B". Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture). For time on pasture, grazing bouts, and bout length, N = 12, for all other variables, N = 28.

	Pasture Sequence (AM → PM)		*P* value
	A (5→2 sp)	B (2→5 sp)	
Total Time on Pasture (min)	761.63 (±31.64)	712.95 (±31.64)	0.29
Grazing Bouts/day	2.96 (±0.17)	2.75 (±0.17)	0.40
Bout Length (min)	287.09 (±20.53)	297.38 (±20.53)	0.73
Milkings/day	2.36 (±0.06)	2.37 (±0.06)	0.89
Milk Yield (kg/milking)	8.02 (±0.29)	7.99 (±0.29)	0.95
Milk Yield (kg/day)	18.14 (±0.87)	18.12 (±0.87)	0.99
Fat (%)	3.86 (±0.14)	3.85 (±0.14)	0.96
Protein (%)	2.73 (±0.05)	2.70 (±0.05)	0.68
Solids (%)	5.49 (±0.06)	5.45 (±0.06)	0.65
SCC (cells x 10^3/mL)	324.2 (±99.5)	277.1 (±99.4)	0.74

Pasture rotation sequence had no effect ($P > 0.05$) on the herds' overall milkings or milk production (Table 3.8), however, AMS occupancy was lower ($P = 0.03$) when animals grazed the 2-species pasture mixture in the morning, and the 5-species mixture in the evening (Table 3.8).

Table 3.8. Daily Automated Milking System (AMS) performance variables (±SE) with significance ($P < 0.05$) for difference between herds of 48 (±3) dairy cows grazed on two pasture rotation sequences: A 5-species pasture mixture during the morning (0500-1300h) and a 2-species pasture mixture during the afternoon and evening (1300-0500h), "Sequence A," or the reverse, a 2-species pasture mixture during the morning and 5-species during the afternoon and evening, "Sequence B". Pasture mixtures consisted of orchard grass, tall fescue, red clover, white clover and alfalfa (5-species mixture), and perennial ryegrass and white clover (2-species mixture).

	Pasture Sequence (AM → PM)		*P* value
	A (5→2 sp)	B (2→5 sp)	
Milkings	105.92 (±3.25)	108.75 (±3.25)	0.648
Milk Yield (kg)	795.08 (±9.71)	785.10 (±9.71)	0.60
Occupancy (%)	55.19 (±6.02)	52.53 (±6.02)	0.807

DISCUSSION

Foraging patterns can be described at a range of spatial scales, from a bite, to a localized patch of forage items, to a broad region in which an animal searches for food (Senft et al., 1987; Bailey et al., 1996; Kotliar and Wiens, 1990). Different foraging patterns may be observed depending on the strength of the animal's response to variation at each scale. Animals adjust their foraging behaviors in response to both immediate and long-term dietary rewards (Senft et al., 1987). At a fine scale, generalist herbivores may respond to either quality or quantity of a particular forage item, and modify selection based on the immediate availability of other forage items.

In this study, cows generally favored the 5-species pasture mixture, or showed no preference at all. This response was counter to our prediction of temporal preferences for the 5-species mixture in the morning and the 2-species mixture containing a HS ryegrass in the

evening. Although the 5-species mixture tended to have lower overall quality than the 2-species mixture, it had greater biomass during the preference trials. The cows may have been responding to a short-term need to maximize intake, thus exhibiting a partial preference for the mixture with higher biomass. During the preference trials, the ratio of the contrasting pasture mixtures was 1:1 based on area, rather than biomass. It is likely that cows were allocating their time based on the relative biomass of each pasture mixture. Perhaps more importantly, the ratio of grasses to legumes was very low in the 2-species mixture. Previous studies found that cows exhibited a partial preference for 70% white clover and 30% perennial ryegrass in adjacent monocultures (Marotti et al., 2002a; Rutter, 2006), however, the composition of our 2-species mixture was 92% white clover and 8% perennial ryegrass. Selecting for a diet that included 30% grass may have been easier in the 5-species mixture, which had a nearly equal proportion of grasses and legumes.

It is unclear why cows in herd 2 showed a strong preference against the 2-species mixture while herd 1 exhibited no preference. We examined forage samples from pastures grazed by each herd and found no apparent differences in quality (CP, NDF) or biomass. Cows increased their preference for the 5-species mixture during the second preference trial. Due to drought, average biomass across the farm dropped through the end of July. During the first preference trial (6/18/11-6/20/11), average biomass (kg DM/ha) was nearly 1900, but during the second trial (7/4/11-7/6/11), biomass had dropped below 1700 (Figure 3.2). Again, animals may have been allocating their time to areas with greater biomass, with quantity rather than quality being the key factor in foraging decisions.
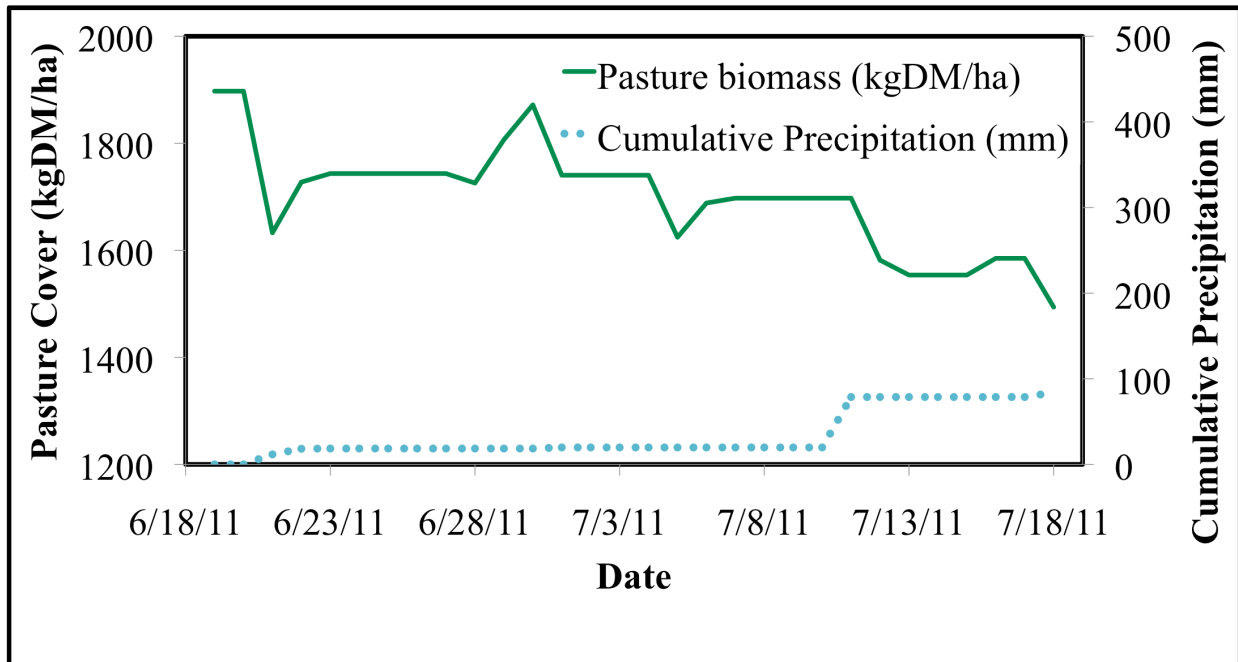
Figure 3.2. Average pasture biomass and cumulative precipitation throughout the study period (18 June 2011 – 19 July 2011) of an experiment on temporal grazing behaviors of dairy cows.

During the pasture rotation study, cows showed selectivity for the 2-species mixture in the evening, as expected. However, they also showed selectivity for the 5-species mixture regardless of time of day. As we observed in the preference trial, animals were likely selecting for the 5-species mixture based on biomass, regardless of time of day. The temporal selectivity for both species mixtures during the evening may indicate a response to accumulation of WSCs in the evening as noted for both orchard grass (Griggs et al., 2007) and perennial ryegrass (Taweel et al., 2005), but more research is required to confirm this observation. Previous research suggests that HS grasses may show variation in the degree to which the HS trait is actually expressed (Edwards et al., 2007). Although some cultivars have successfully increased production in the UK and New Zealand, this response has not been previously tested in North America. Furthermore, although low temperatures typically increase WSC content in these HS

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cultivars, this increase may only be significant after a sustained period of cool, short days (Parsons et al., 2004), which was not the case in this study.

Abiotic factors such as distance between forage patches (Chapter 2), and temperature (Chapter 4) play a key role in broad-scale foraging decisions. The pasture rotation study differed from the preference trial in that paddocks containing the contrasting species mixtures were separated by a greater distance, rather than immediately adjacent to one another. We observed no changes in behavior or production when offering different sequences of forage species. Among generalist herbivores, selectivity for particular forage species may occur at a finer spatial scale, but at a broad scale, distance may play a more important role in patch selection. We did observe a general increase in selectivity for both species mixtures during the afternoon grazing bout. This may have been reflective of a preference for when to graze, rather than what to graze. Animals spent more time in the barn during midday, which may have been due to increased temperatures during the study period (daily temperatures peaked at 29 ± 0.7 °C). As a result, the animals were likely allocating a greater amount of time towards grazing during the coolest hours of the day (daily minimum temperature was 16 ± 0.5 °C).

CONCLUSIONS

At the spatial scale of 1 ha paddocks, dairy cows do not show any apparent short-term behavioral or milk production responses to varying species mixtures. Cows tended to favor the species mixture lacking a HS grass species, although previous studies suggest that this may have been a means of maximizing intake rate, since the sward containing HS grass had lower biomass. Cows also exhibited strong selectivity for both species mixtures during the evening hours, suggesting that time of day, rather than forage species, plays an important role in their broad scale foraging decisions.

CHAPTER 4

EFFECTS OF DYNAMIC SUPPLEMENTATION ON MOVEMENT BEHAVIORS OF TWO BREEDS OF CATTLE IN A FREE-TRAFFIC PASTURE SYSTEM

Abstract

In pasture-based dairies, animal behavior and production are largely affected by feed management. In the context of automated milking systems (AMS) in particular, careful management of cow traffic is central to achieving production goals. Different cattle breeds may also be better adapted to certain feeding systems. Two herds of 40 United States Holstein (USH) and 7 New Zealand Friesian (NZF) cows each received one of two different pasture-based feeding system treatments: High stocking rate (HSR) with access to 16 ha pasture in addition to partial total mixed ration (pTMR) and concentrate supplement in the barn, and low stocking rate (LSR) with access to 24 ha pasture with concentrate supplementation. Cattle movement behaviors and milk production were recorded for 24 days, using global positioning system (GPS) units and AMS. Animals spent less time grazing in the HSR treatment ($P < 0.01$). However, grazing bout frequency, milking frequency, milk production did not differ between feeding systems ($P > 0.05$). Breed affected milk yield, with NZF cattle producing significantly less than USH cattle ($P < 0.01$). Time spent grazing, grazing bout frequency, and milking frequency were not affected by breed alone ($P > 0.05$). There was, however, a significant breed by treatment interaction ($P < 0.01$) on time spent grazing. NZF cattle spent more time grazing in the HSR treatment, while USH cattle spent more time grazing in the LSR treatment. Feeding system and breed play a role in behavior and milk production, but did not significantly impact as many variables as expected. At a broad spatial scale (as was the case in this study) abiotic factors such as temperature may have a greater effect than feeding system or breed on behavior and production variables.

INTRODUCTION

Background

The current generation of US dairy farmers has seen perhaps the most dramatic change to date in the way milk is produced and harvested. Due to rising feed, fuel and labor costs, as well as rising consumer demand, the dairy industry has shifted from many small, family farms to few large, factory farms (USDA, 2007). Faced with a highly competitive market, small dairies are often forced to either grow or sell out. If small farmers want to remain competitive, they must reduce the costs of feed, fuel, and labor, while maintaining adequate production.

One management practice that reduces both fuel and feed costs is the adoption of pasture-based feeding systems. In a pasture-based system, less feed is imported to the farm, and less waste is exported. Pasture diets reduce milk yield, but they can also reduce costs such that net income is comparable or higher than that of conventional dairies (Dartt et al., 1999). Depending on the management approach, pasture-based farming can range from nearly 100% reliance on pasture for feed, to a diet that is heavily supplemented with concentrates (> 2000 kg/cow/yr) or harvested forage offered as partial mixed ration (Little, 2011). Some benefits of supplementing a pasture-based diet include higher milk yield and adaptability during seasonal changes in pasture growth (Kolver and Muller, 1998; Fulkerson et al., 2005). Along with partial supplementation, another potential method for maintaining production is choosing animals that perform well in specific feeding systems. Pasture grazing is more commonly practiced in countries such as Australia and New Zealand, and cattle in these countries differ from those in the US. Research suggests that New Zealand strains of cattle may perform better than United States strains of cattle in pasture systems, while the reverse seems to be true in systems with high supplementation (Horan et al., 2005, 2006; Macdonald et al., 2008). For instance, New Zealand

cattle can achieve maximum feed-conversion efficiency (milk production per feed intake) on a primarily pasture-based system, while United States Holstein strains tend to require some diet supplementation to achieve maximum production (Kolver et al., 1998; Bargo et al., 2002). An appropriate combination of animals and feeding system can reduce feed and fuel costs, helping small farmers to remain competitive in today's dairy industry.

Another strategy for remaining competitive is reducing labor costs with new technologies including voluntary, automated milking systems (AMS). The AMS eliminates the need for manual labor to milk cows, and allows for high-producing animals to be milked more frequently, both decreasing labor demands and increasing milk production. A combination of AMS with a pasture-based feeding system has the potential to reduce the costs of labor, fuel, and feed, but in practice, this combination often results in decreased milk yield (Utsumi, 2011). Animals lose the motivation to voluntarily visit the milking unit when they must travel the distance from the pasture to the milking barn, resulting in decreased milking frequency and production (Ketelaar-de Lauwere et al., 1999; Utsumi, 2011). Various feed incentives have been used to maintain production in combined pasture and AMS farms, with mixed results (Jago et al., 2002; Davis et al., 2007; Lyons, 2011; Chapter 2). Supplementing pasture-based feeding systems with additional forage and concentrate may be an option for resolving the problem of decreased milking frequency and production. Diet supplementation not only increases dry matter intake, it also has the potential to encourage more frequent visits to the milking barn and AMS. With a better understanding of what motivates cows' movements and behavior in various pasture-based systems, farmers will be able to make informed management decisions, optimizing milk production, and reducing cost.

Objectives

The objectives of this study were two-fold. First, we sought to determine how two different pasture-based feeding systems, a low stocking rate system, and a high stocking rate system with supplemented ration, would affect movement behaviors and milk production. We expected supplementation to increase milking frequency and potentially milk yield, due to greater time spent in the barn. We also expected supplementation to lower the number and length of grazing bouts on pasture. Our second objective was to determine whether breed influenced foraging behavior and milk production in a pasture-based feeding system with AMS. Compared with United States Holstein cattle, we expected New Zealand Friesian cattle to have lower production. We also expected New Zealand cattle to spend more time on pasture and to make more frequent visits to the pasture.

MATERIALS AND METHODS

Study Site

The study was conducted at the W.K. Kellogg Biological Station (KBS) Dairy in Hickory Corners, Michigan. Prior to the start of this study, protocols were reviewed and approved by the MSU Institutional Animal Care and Use Committee (IACUC). During the study period, the lactating herd included 94 (±8 on any given day) lactating Holstein-Friesian cattle. The farm has 64 ha of pasture, divided into 8 blocks of paddocks, which are connected by a sand laneway to a centrally located milking barn (Figure 4.1). The dairy uses an automatic milking system (AMS), equipped with two single-stall A3 Lely Astronaut robotic milkers (Lely Industries, N.V., Maassluis, Netherlands). The KBS herd was transitioned from a conventional, confinement system to an AMS in 2009, and to a pasture-based feeding system in 2010. The animals are

rotationally grazed for seven to eight months of the year, and are fed total mixed ration (TMR) and concentrate, and housed in a free-stall barn during the winter. Lely Grazeway exit gates (Lely Industries, N.V., Maassluis, Netherlands) regulate movement from the barn to the pasture. The split-barn design, with two herds, is conducive to experimental comparisons of various dairy management strategies.

The KBS pasture includes two diversity treatments of contrasting species composition, seasonality, forage growth, and quality, which were seeded in adjacent 1 ha strips at varying distances from the dairy barn. The high diversity paddocks were seeded in 2008 and include red clover (*Trifolium pratense*), white clover (*T. repens*), alfalfa (*Medicago sativa*), orchard grass (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*). The low diversity paddocks were seeded in 2010, and contain white clover (*T. repens*) and perennial ryegrass (*Lolium perenne*). Both pasture types were seeded with equal parts grass and legume.

Average temperature during the study was 18.9 °C, and average precipitation was 2.5 mm/day. Climate data were collected at the KBS Long-Term Ecological Research (LTER) weather station, less than 1 km from the experimental site.
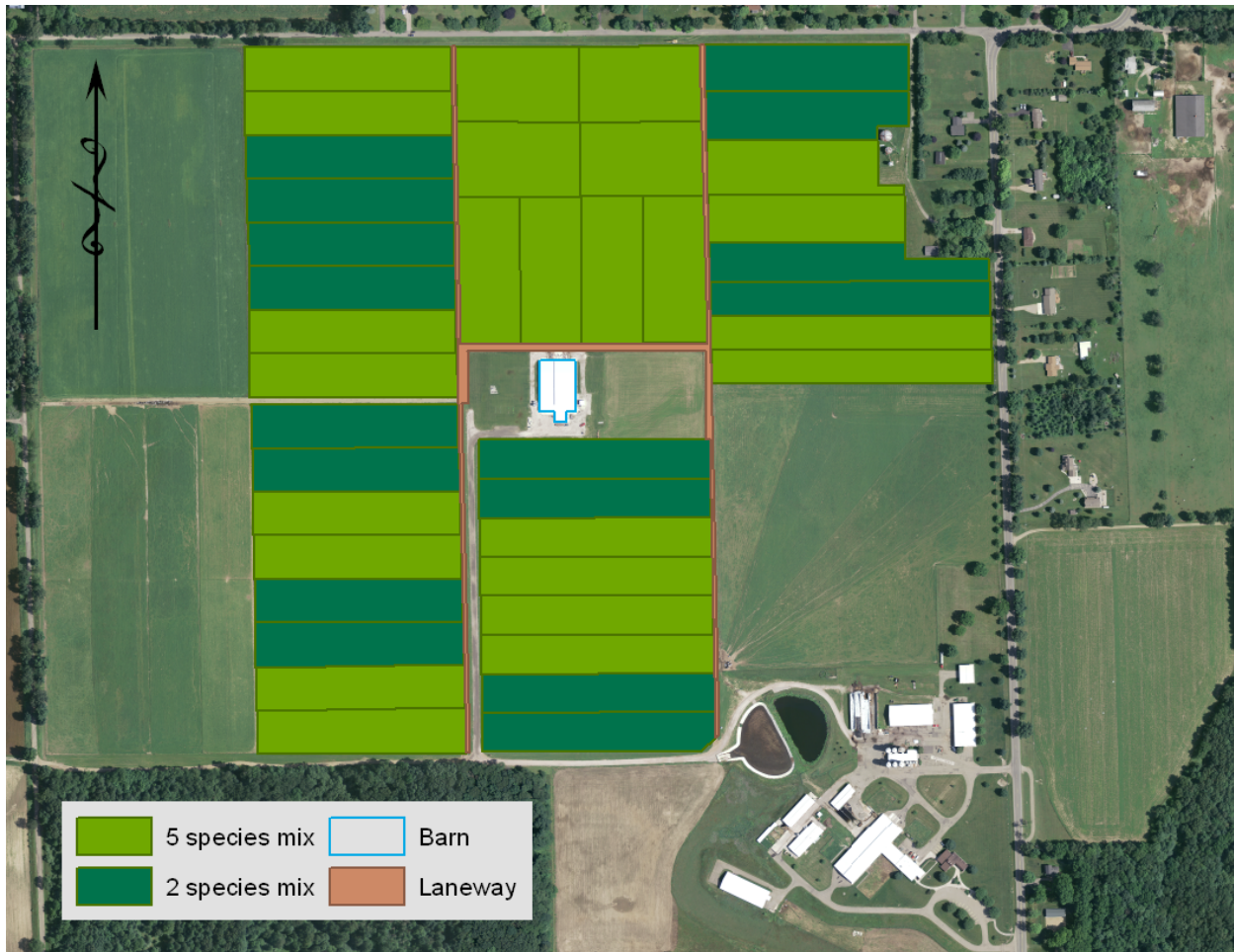
Figure 4.1. The Kellogg Biological Station (KBS) pasture dairy. Paddocks used in this study are highlighted with 2 colors of green, denoting 2 species mixtures. A sand laneway leads to a centrally located milking barn.

Experimental design

For this study, we applied a 2 x 2 factorial arrangement of two Holstein-Friesian cattle genotypes and two pasture-based feeding systems in a completely randomized design. All data for this study were collected between 12 August and 15 September 2011.

Animals and Grazing Management

Two herds, each with 40 (±3 on any given day) United States Holstein (USH) cows and 7 New Zealand Friesian (NZF) cows were used in the study. From late summer to late fall (~August-November 2011), herds were assigned to 2 management treatments with contrasting feeding systems and stocking rates. Herd 1 was managed at a high stocking rate (HSR; 2.89 cows/ha), with access to 16 ha pasture, which made up 52% of the diet (9.8 ± 1.8 kg/cow/day), with the remainder of feed provided as ground corn (1.1 ± 0.1 kg/cow/day), commercial pellet (3.3 ± 0.2 kg/cow/day; CP 17.6 %, NDF 42.8%), and dynamically-supplemented partial total mixed ration (pTMR) at the bunk (4.9 ± 0.1 kg/cow/day; CP 14.8 %, NDF 32%). Rate of pTMR supplementation was adjusted weekly to account for fluctuations in pasture growth rates. Herd 2 was managed at a low stocking rate (LSR; 1.92 cow/ha), with access to 24 ha pasture, which made up 80% of the diet, with the remainder of feed provided as ground corn (1.0 ± 0.1 kg/cow/day) and commercial pellet (3.2 ± 0.2 kg/cow/day). Target feed allocation per animal was ~22 kg dry matter (DM) per day. Automatic Cosmix feeders (Lely Industries, N.V., Maassluis, Netherlands) in the milking barn were used to regulate the amount of ground corn consumed per individual. Commercial pellet concentrate was fed in the AMS milking stall at a rate of 1 kg per 6 kg of milk yield. Lely T4C software (Lely Industries, N.V., Maassluis, Netherlands) was used to manage pellet distribution to the animals.

Herds were rotationally grazed in a free-traffic pasture system. Fresh pasture breaks were offered at 0500 h each day. The HSR treatment had access to one half of a 1 ha paddock per day. A temporary fence was used to prevent cows grazing the second half of the paddock. On the second day of grazing in the same paddock, the temporary fence was removed and cows

accessed the second half of the paddock. The LSR system grazed 1 paddock per day. Rotational grazing of paddocks was based on approximate targets of 2400 and of 1600 ± 200 kg DM for pre- and post- grazing pasture biomass, respectively. When necessary, pastures were grazed based on stage of maturity using the number of extended leaf per tiller in grasses and flower percentage in legumes.

Lely Grazeway gates (Lely Industries, N.V., Maassluis, Netherlands) regulated exit from the milking barn. Exit permission was granted based on either a minimum milk yield of 9.1 kg/milking or a minimum milking interval. Expected milking intervals varied with a given animal's number of days into lactation (days in milk; DIM), based on a maximum and minimum number of milkings. The milking setting used was maximum and minimum number of milkings of 5 and 4 for cows < 30 DIM, 4 and 3 for cows between 31 DIM and 30 days prior to "dry off" (i.e. end of lactation), and, 3 and 2 for cows within 29 days of dry off, respectively. Dry off occurred when cows reached 252 days of gestation.

Pasture Sampling

Pre- and post-grazing pasture height and herbage mass in both of the pasture types were determined weekly, using a laser-based rapid pasture meter (C-Dax Agricultural Solutions, Ltd., Palmerston North, NZ), and daily, using a F400 rising plate meter (RPM; Farmworks, Palmerson North, NZ). Data collected with the C-dax meter was analyzed with FarmKeeper software (Farmkeeper Pty Ltd, Hamilton, New Zealand) to determine amount of pTMR fed based on pasture growth rate change (See Nieman, 2012 for details). A total of 30 RPM readings per paddock were used to estimate the pre- and post- grazing herbage mass. Average intake rate (kg

DM / ha) was determined with the agronomic difference method (Coates and Penning, 2000) from pre- and post-grazing forage biomass estimates.

Animal Sampling

From each herd, 6 cows (3 USH + 3 NZF) balanced for parity (USH, 1.67 ±0.21; NZF, 1 ±0.00), DIM (USH, 176 ±6; NZF, 169 ±3), body weight (USH, 570 ±14 kg; NZF, 394 ±9 kg), and previous milk yield (USH, 28.3 ±3.1 kg; NZF, 14.5 ±1.5 kg) were selected as test subjects. All study animals were successfully bred prior to the study. Test animals were fitted with Global Positioning System (GPS) collars equipped with temperature, head position, Y-axis, and X-axis sensors (Lotek Wireless Inc., Newmarket, Ontario, Canada). The GPS units took a location fix every 5 minutes. Prior to analysis, GPS fixes were differentially corrected with N4 v.1.1895 software (Lotek Engineering Inc., Newmarket, ON, Canada) based on GPS data from the National Geodetic Survey continuously operating reference station at Plainwell, Michigan (MIPW, www.ngs.noaa.gov/CORS/). Differentially corrected location points were then used to determine horizontal distance walked, duration and frequency of feeding bouts, as well as bout length (ArcGIS 9.3, Environmental Systems Research Inc., Redlands, CA, USA). For the purpose of this study, a "feeding bout" was defined as series of consecutive location fixes within a given paddock. A return to the barn, indicated by a series of fixes in the laneway and milking barn, concluded a feeding bout, and any subsequent fixes within a paddock were defined as a new feeding bout. "Bout length" was defined as the time from the first location fix occurring within a paddock to the final consecutive location fix occurring within that paddock.

T4C software (Lely Industries, N.V., Maassluis, Netherlands) was used to retrieve average milk yield and milking frequency data collected by the AMS on a daily basis. Average daily temperature and precipitation data from the KBS Long-Term Ecological Research (LTER)

weather station site was collected to evaluate the potential for climatic effects on movement behaviors and milk yield. The LTER weather station is located within 1 km from the experimental site. All animal movement, milk and weather data were collected for 34 days, with a 1-day break between days 16 and 17 for GPS collar maintenance and battery replacement.

Statistical Analyses

All analyses of the data were performed using SAS v.9.3 (Statistical Analysis Software, Cary, NC). When appropriate, results are reported as least square means ± standard error of the mean (SE). Results were considered statistically significant at a probability of $\alpha < 0.05$.

Artifacts

Due to the fact that the cows were adapted to receiving a fresh pasture break at approximately 0500h each day, and often spent the night in the pasture, a "day" was defined as the 24-hour period from 0500h on a given day to 0459h on the following day. Measurements of grazing bout frequency, total distance traveled, and average bout length were recorded for each day. On a day-by-day basis, some animals extended their stays in the pasture allocation from the previous day beyond 0500h. To avoid counting this time as a new grazing bout, GPS fixes were assessed by day from the first fix located within the milking barn after 0459h to the first fix within the barn after 0459h on the following day.

One study animal lost its GPS collar for part of 1 day during the study. The collar was recovered and reattached the same day. For this day, data from this collar were excluded from analysis.

Movement Behaviors and Milk Production

Data were analyzed with the MIXED model procedure, using compound symmetry, autoregressive order 1 or unstructured covariance structure where appropriate (Littell et al., 1996), and the Kenward & Rogers (1997) method for degrees of freedom. The effects of cow, feeding system (stocking rate), and day on movement behaviors (bout frequency, bout length, and milking frequency) and production (milk yield, AMS occupancy, and milk quality) were analyzed in the following model:

$$Y_{ijkl} = \mu + \alpha_i + \beta_i + \gamma_k + \delta_l + \beta_i*\gamma_j + \beta_i*\delta_l + \gamma_k*\delta_l + \beta_i*\gamma_j*\delta_l + \varepsilon_{ijkl}$$

Where

Y_{ijkl} = movement behavior or production variable of interest;

μ = overall mean;

α_i = random effect of cow (i = 12 GPS collared cows);

β_i = breed (j = 2 breeds, NZF or USH);

γ_k = feeding system (k = 2 feeding systems, pTMR or PC);

δ_l = day (l = 34 days); and

ε_{ijkl} = residual error.

Movement Behaviors and Milk Production

Between the two feeding systems, time spent grazing was the only behavior that changed.

Total time on pasture, and individual grazing bout lengths were both significantly shorter when

diets were supplemented with pTMR (Table 4.1). Number of grazing bouts, milkings, and milk

yield were not directly ($P > 0.2$) affected by feeding system (Table 4.1). Additionally, we found

that time spent on pasture significantly varied ($P < 0.0001$) by day (Figure 4.2). Excluding milk

yield per milking, all variables measured varied by day ($P < 0.01$), however, no patterns were

apparent aside from total time on pasture, which tended to vary in response to temperature

(Figure 4.2).

Table 4.1. Movement behaviors and milk yield (±SE) of dairy cows in a pasture-based system with automated milking, with significance ($P < 0.05$) for difference between two feeding systems (pTMR, 52% pasture + 48% partial total mixed ration and concentrate; PC, 80% pasture + 20% concentrate). N = 6.

	Feeding system		*P* value
	pTMR	PC	
Total Time on Pasture (min)	765.10 (±22.26)	990.64 (±22.28)	< 0.0001
Grazing Bouts/day	3.07 (±0.21)	2.90 (±0.21)	0.591
Bout Length (min)	277.12 (±24.14)	394.71 (±24.15)	< 0.009
Milkings	2.41 (±0.19)	2.17 (±0.19)	0.386
Milk Yield (kg/milking)	8.92 (±1.02)	10.77 (±1.02)	0.230
Milk Yield (kg/day)	21.03 (±4.13)	21.73 (±2.93)	0.893
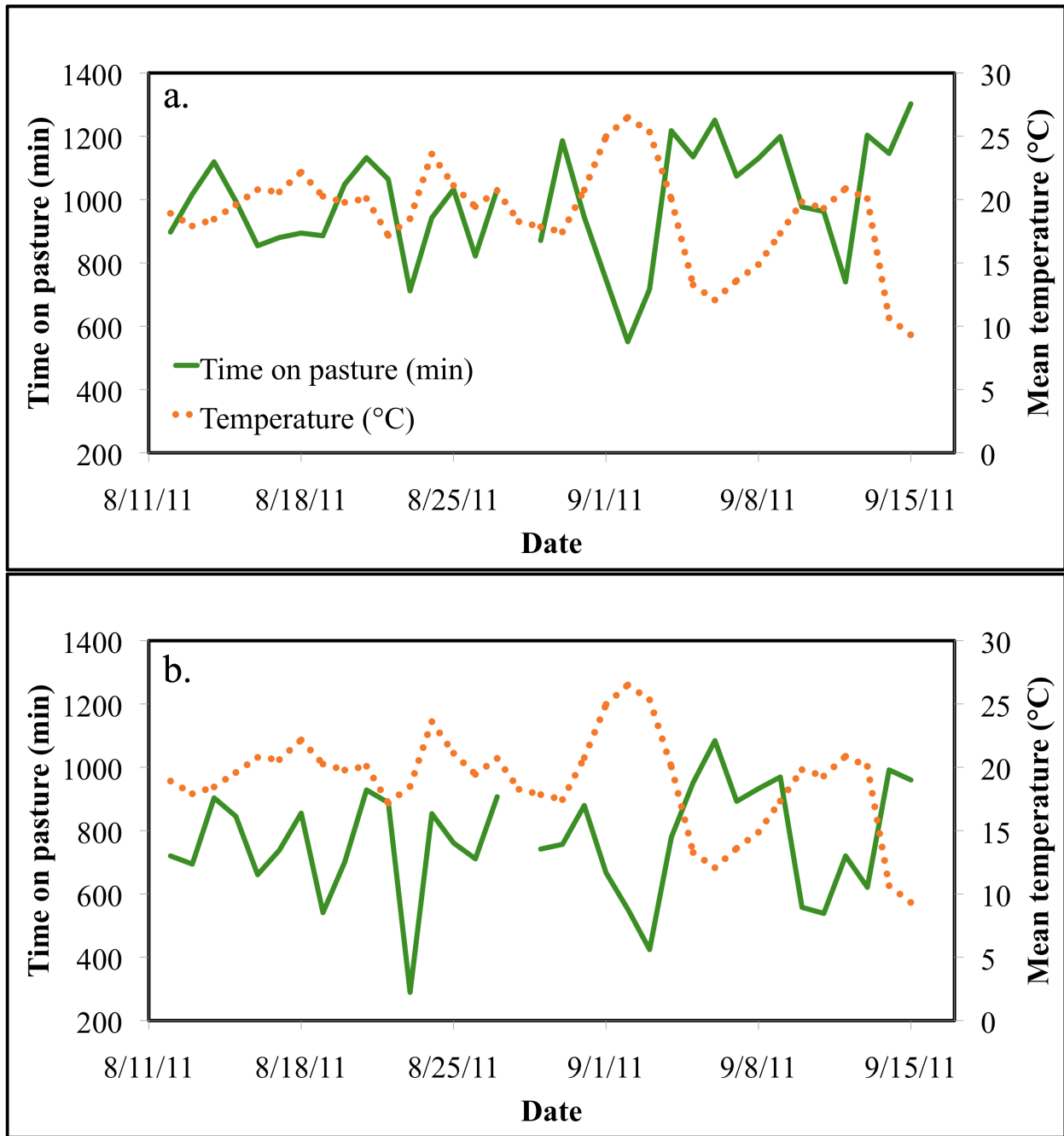
Figure 4.2. Mean daily temperature and time spent on pasture by dairy cows grazed with 2 pasture-based feeding systems (panel a: PC, pasture + concentrate; panel b: pTMR, partial totally mixed ration). Data for time spent on pasture were unavailable on 28 August due to GPS collar removal for maintenance and battery replacement.

Breed had no influence on movement behaviors or milkings (Table 4.2). Only milk yield was affected by breed, with NZF cattle producing less than USH (Table 4.2). Although breed had

no direct effect on movement behaviors, we did find a breed by treatment interaction ($P < 0.007$)

for total time spent on pasture (Figure 4.3).

Table 4.2. Movement behaviors and milk yield (±SE) with significance ($P < 0.05$) for difference between two breeds of cattle (USH, United States Holstein; NZF, New Zealand Friesian) grazed in a pasture-based system with voluntary automated milking. N = 6.

	Breed		*P* value
	USH	NZF	
Total Time on Pasture (min)	860.47 (±22.26)	895.27 (±22.28)	0.301
Grazing bouts/day	2.73 (±0.21)	3.24 (±0.21)	0.118
Bout Length (min)	364.60 (±24.14)	307.23 (±24.15)	0.131
Milkings/day	2.46 (±0.19)	2.12 (±0.19)	0.236
Milk Yield (kg/milking)	12.23 (±0.95)	7.46 (±0.96)	< 0.008
Milk Yield (kg/day)	28.27 (±1.31)	14.5 (±2.52)	< 0.002
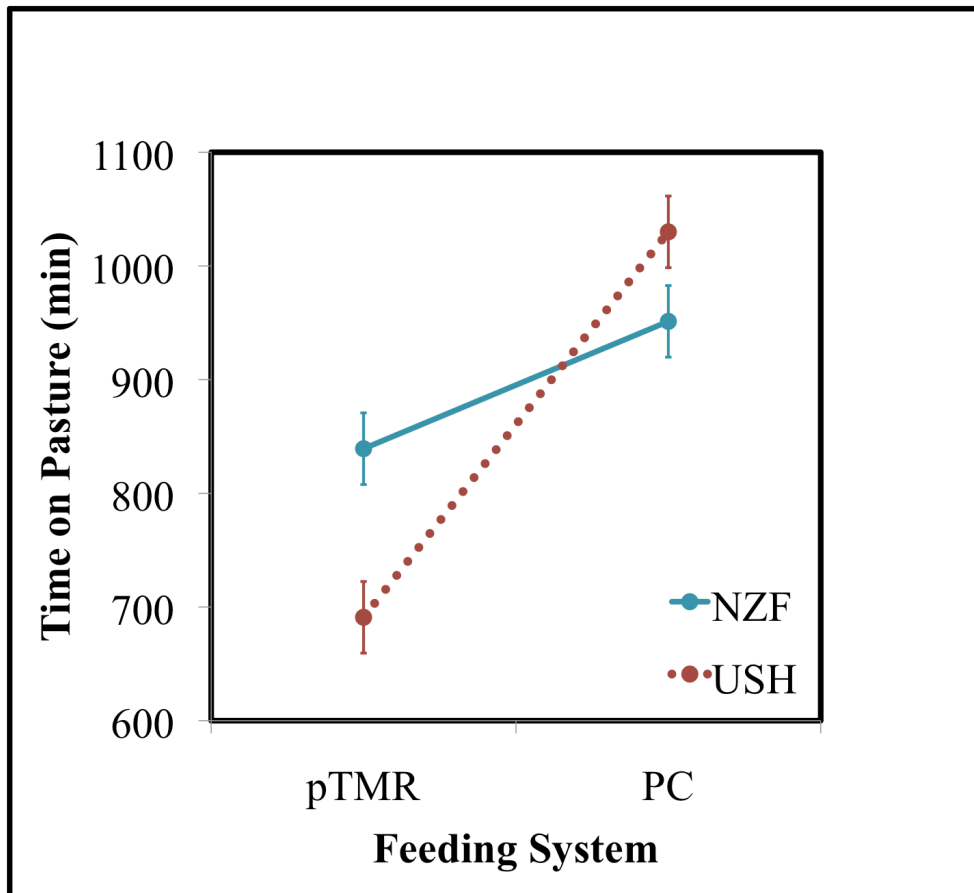
Figure 4.3. Time spent on pasture by New Zealand Friesian (NZF) and United States Holstein (USH) cows in two different pasture-based feeding systems (pTMR, 52% pasture + 48% partial total mixed ration and concentrate; PC, 80% pasture + 20% concentrate).

DISCUSSION

Implementing different management strategies to maintain milk production while reducing costs of feed, fuel, and labor could help small farmers remain competitive in an ever-changing dairy industry. Combining AMS with pasture-based feeding systems is a relatively new management strategy, and farmers using this strategy do not always achieve desired production goals (Ketelaar-de Lauwere et al., 1999; Utsumi, 2011). The aim of this study was to better understand how animals respond to different feeding systems in the context of AMS. We examined how 2 different strains of cattle responded to 2 different pasture-based feeding systems. In general, broad-scale movements of cattle are influenced more strongly by abiotic factors such as distance between paddocks (Chapter 2), while biotic factors such as forage heterogeneity and quality only seem to affect fine-scale foraging decisions (Chapter 3). In this study, we found mixed support for this conclusion.

As expected, animals managed with a pasture-based diet that was dynamically supplemented with both pTMR and concentrate spent less time grazing (per bout, and overall) than those that did not receive pTMR. However, average number of bouts did not differ between the two feeding systems. There was also no difference in milking frequency or production between feeding systems. We expect that animals in the pasture-concentrate LSR treatment were making up dry matter intake by spending more time on pasture. A reduction in grazing time by 320 min was previously reported for cows fed in a forced grazing system with orchard grass pasture (Bargo et al., 2002). Supplementation with pTMR may also affect AMS visitations if other activities in addition to grazing are also changed. It is likely that individual AMS milking frequencies were not significantly different between treatments due to the low number of test subjects (6 cows per treatment group).

From an ecological standpoint, the TMR supplement acts as a patch of forage that differs from the patches available in the pasture, creating broad-scale heterogeneity in the HSR treatment. Cows responded to this difference by altering the amount of time they spent grazing, but other movement behaviors were not affected. The fact that cows showed some response to feeding treatments indicates that biotic factors may have an influence on broad-scale movements. Interestingly, daily variation in time spent grazing appeared to be inversely related to daily variations in temperature, suggesting that this abiotic factor also plays an important role in animal movements.

As predicted, USH cattle had greater production than NZF cattle, however there were no differences in milking frequency or movement behaviors between the two breeds. Furthermore, breed had almost no influence on animal performance in contrasting feeding systems. We found one breed by feeding system interaction, in time spent on pasture. Overall, both breeds spent more time on pasture in the feeding system lacking pTMR supplement (LSR); however, time spent on pasture by NZF cattle was less variable between the two feeding systems. When receiving a pTMR supplement, USH cattle spent less time on pasture than NZF cattle, but when the diet was primarily pasture-based, USH cattle spent more time on pasture than NZF. This behavior implies that because USH cattle have greater energetic requirements (Horan et al., 2006), they rely more heavily on supplements in pasture-based systems.

For small farmers, pasture-based feeding systems provide an affordable alternative to more costly, conventional production methods. However, relying primarily on a grass-based feed source comes at a cost, as it also tends to reduce production. A hybrid system that supplements a pasture-based diet with TMR may be one solution to reducing feed costs while still maintaining relatively high production (Little, 2011). In the context of AMS, a dynamically supplemented

pTMR did not seem to alter milking frequency or yield, although further confirmation of this finding will be valuable, due to the small sample size in this study. Breed also had little effect on animal performance in the context of AMS, with only the total time spent grazing varying based on an interaction between breed and feeding system. Additional research on milk quality and other animal performance variables will be valuable for comparing the benefits of these two contrasting feeding systems, particularly in the context of AMS. Although dairy production is changing dramatically, various combinations of breed, milking system, and feeding system provide several management options that allow small dairy farms the chance to persist and compete in the modern dairy industry.

CHAPTER 5

IMPLICATIONS AND FUTURE RESEARCH

The aim of this thesis research was to better understand how dairy cows respond to environmental factors in the context of a pasture-based system with automated milking. Specifically, we examined factors that affected grazing behaviors, and in turn, movement between the pasture and AMS. The ability to manage some environmental variables in order to encourage voluntary visits to the AMS is important to the success of a pasture-based, AMS operation.

The first study evaluated the effects of distance and broad-scale forage heterogeneity on animal movements. Consistent with ecological theory, cows responded to distance by spending more time grazing in pastures that required a higher energy investment in travel time (i.e., the pastures farthest away from the AMS). As cows took longer grazing bouts, intervals between voluntary milkings increased, leading to a drop in milking frequency. In turn, decreased milking frequency tended to reduce milk yield. This response was not surprising, but has important implications for management. A rotational grazing system will inevitably require animals to walk varying distances, depending on which paddocks have sufficient forage for grazing. Strategic management of grazing rotations, however, could help to mitigate the effects of increased bout lengths. For instance, a manager might choose to alternate between close and far paddocks on successive days to avoid any sustained decreases in milking frequency. A farm design that allocates equal areas of pasture on either side of the milking barn would also help to minimize the distance of the farthest paddocks used in regular rotations. It might also be valuable to investigate how cows would respond to a rotation system that offered three or more spatially

separate pasture breaks per day. This could be strategy for encouraging shorter, more frequent bouts and in turn, more frequent visits to the AMS.

Although cows altered their broad-scale movement patterns in response to distance, they did not respond to rotation sequences that included forage species heterogeneity at a broad scale. Previous studies indicate that cows and other large ruminants will select for variety in their diets, however, this has only been consistently observed at a fine scale. Since the pastures used in this study already contained a variety of grasses and legumes, the cows may have been finding adequate diet variety within a given paddock. The option of a unique forage item across the farm may have not been enough to entice the animals to invest in traveling to it.

The goal of the second study was to determine whether time of day might factor in to foraging behaviors. Increased concentrations of plant non-structural carbohydrates (NSC) toward the end of the day were possibly what prompted cows to allocate more time toward grazing during afternoon and evening hours. However, any number of other factors may have also affected the cows' decisions on when to graze. It is unclear whether cows can detect changes in NSC concentrations based on plant palatability, or whether increased NSC concentrations are simply a proxy for another preferred physiological characteristic, such as texture. Further research on cow responses to temperature, humidity, and other factors which may vary with time of day will be necessary to confirm that NSC concentrations are, in fact, a driver in the cows' motivation to graze during evening hours.

Although cows did not show a temporal preference between contrasting pasture types, they did tend to favor the pasture mixture with greater species diversity, regardless of time of day. These results suggest that cows may select for greater biodiversity, when available. However, unforeseen environmental conditions (e.g. drought) before and during the study period

led to differences in biomass, forage quality, and grass-legume ratios between the two species mixtures, so a number of factors were likely influencing preference. While results from this study should be interpreted with caution, it still offers valuable preliminary evidence that cows alter their foraging behavior in response to contrasting pastures. Additional research examining responses to a broader range of diversity mixtures will be valuable both for understanding the ecology of dairy cows, and for further improving methods for managing cow traffic in pasture systems.

The final study examined the behaviors of two breeds of cattle across two different feeding systems. Some previous research suggests that United States Holsteins (USH) perform better in systems with high supplementation, while New Zealand Friesians (NZF) are better adapted to pasture-based systems. Among the variables we measured, only the total time spent grazing was affected by an interaction between feeding system and breed. Although both breeds spent more time grazing in the system lacking pTMR supplementation, NZF cows were less variable between systems with or without supplementation. In the system with pTMR supplementation, NZF cows spent more time on pasture than USH cows, but in the absence of supplementation, the USH cows compensated by spending much more time on pasture. This response may be indicative of NZF cows' ability to achieve maximum intake with minimal supplementation. However, anecdotal observations of social behavior during the study suggested that NZF animals were typically at the bottom of a dominance hierarchy within the herd. Due to their smaller size, NZF cows may have been bullied by the USH cows at the pTMR feeding site in the barn, and may have compensated by spending more time on pasture. Research comparing two separate herds of USH and NZF cows would eliminate this possibility. Future research

examining social behavior patterns will also be valuable for determining whether dominant cows play a role in enticing or discouraging other cows from making visits to the pasture or the AMS.

Animals respond to different factors of their environment at a variety of scales. While abiotic factors such as weather, time, and traveling distance may affect timing and duration of foraging bouts, biotic factors, such as botanical composition and physiology, may play a more important role in fine-scale movements. Many studies have examined the foraging behaviors of dairy cows at a localized level. The research in this project focused on broad-scale movements in response to forage. However, a decision made at one level – for instance, which patch to forage – will determine the options available when an animal makes foraging decisions at a finer scale – such as which plant to eat. An integrative study that examines both fine- and broad-scale decisions would be valuable for further understanding the hierarchy of levels on which animals interact with their environment.

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